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Peatland response to climate warming after the Little Ice Age

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Tiivistelmä/Referat – Abstract

Pohjoiset suoalueet muodostavat merkittävän hiilivaraston, joihin on sitoutuneena noin 30 % maapallon maaperän hiilestä. Ilmasto on merkittävin soiden ekologiaa säätelevä tekijä. Ilmastonmuutos vaikuttaa erityisen voimakkaasti pohjoisiin alueisiin. Takaisinkytkennät soiden ja ilmaston välillä tekevät tästä suhteesta vaikeasti ennustettavan. Tämä ennakoi suuria muutoksia soiden ekologiaan ja hiilen kiertoon.

Tämän tutkimuksen tavoitteena on ollut selvittää soiden vastetta pikkujääkauden (LIA) jälkeiseen lämpenemiseen ja millainen vaikutus sillä on ollut kyseisiin hiilivarastoihin. Useiden epäsuorien aineistojen ja tarkan suodatan avulla, on tarkoitus kartoittaa tätä kehitystä Suomessa ja Virossa sijaitsevilla tutkimusalueilla. Tutkimus kohdistuu ombrotrofisten soiden kolmeen erilaiseen mikrohabitaattiin. Vertaan tuloksiani aiempien tutkimusten epätarkempaan dataan saadakseni uusille metodeille tukea ja lisää alueellista kattavuutta. Analyysini pohjautuu 210 Pb-kronologiaan. Kasvien makrofossiilit, nykyinen kasvillisuus, joista *Sphagnum* maksasammalet ovat tärkeimpiä, sekä vedenpinnan korkeudet ovat pohjana mallinnettaessa menneen kasvillisuuden koostumusta ja hydrologiaa. Ikä-syvyysmallit ja vedenpintarekonstruktiot rakentuvat näihin muuttujiin. Myös turpeen C/N ja tiheys mitattiin.

Tutkimuksessa paljastui merkittäviä ja nopeita vaihteluita niin kerrostumisnopeudessa kuin kasvillisuuden koostumuksessakin. Pikkujääkauden jälkeen soiden pinnat ovat kuivuneet ja näihin oloihin paremmin sopeutuneet kasvit ovat syrjäyttäneet kosteampien habitaattien lajeja tehokkaasti. Soiden vaste LIA:n jälkeisiin ilmaston vaihteluihin näyttää olleen kaksivaiheinen. Pikkujääkauden lopussa kosteus ympäristössä lisääntyi. Tätä seurasi ilmaston lämpeneminen ja kahdessa vaiheessa ympäristön kuivuminen. Ilmastonmuutosten yhteensopivuus aikajanalla soiden muutosten kanssa kertoo näiden kahden mahdollisesta yhteydestä. Tulokseni viittaavat siihen, että lyhyen aikavälin muutokset saavat aikaan suuria muutoksia soiden ekologiassa ja pitkällä aikavälillä uhkaavat soiden olemassaoloa.

Muutokset tapahtuvat primääriproduktion, hajoamisen ja paikallisen hydrologian herkän tasapainon järkkyessä. Eri mikrohabitaatit ovat haavoittuvampia ilmaston aiheuttamille muutoksille kuin toiset. Tulevaisuudessa pohjoiset suot tulevat kokemaan yhä suurempia muutoksia ilmastossa. Näiden muutosten kokoluokka ratkaisee sen, onko soiden vaste sitoa yhä enemmän hiiltä ilmakehästä vai muuttuvatko suot päinvastoin hiilen lähteiksi ilmakehään. Samalla suuret määrät soita häviäisi ja hiilivuot ilmakehään kasvaisivat edelleen.

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Tiivistelmä/Referat – Abstract

Northern peatlands are a valuable, volatile carbon stock and hold 30 % global terrestrial organic carbon. Climate is the most important control on peatland ecology. Positive and negative feedback loops between peatlands and climate make this complex relationship. Climate change affects high northern latitudes in particular, making the northern peatlands prone to experience massive changes in ecology. It is unclear exactly how long-term climate change will affect such an integral part of the carbon cycle.

My intent was to produce a reliable study of what kind of response did bogs develop after the Little Ice Age (LIA) and how climate warming has affected these important carbon stocks. This study uses high frequency, multi-proxy, post-LIA peatland response data to map the ecological response of a boreal ombrotrophic peatland ecosystems. Study sites are located in Southern-Finland and Estonia. I concentrate on three distinct micro-habitats. I use low-frequency data from previous studies to compare with my novel data and to give the study more spatial scope. My analysis is structured around a chronology consisting of ^{210}Pb-dates. Plant macrofossil data, present vegetation data, *Sphagnum* mosses as the most important group, and modern water-table data are used to model past plant composition and hydrology. Age-depth models and water-table reconstructions have been created on this basis. Bulk density and C/N ratio were also analysed.

Large and fast paced shifts in accumulation rates and changes in vegetation composition were revealed. After LIA, peatland surfaces have dried and dry-habitat vegetation has increased. I identified a two-step pattern in response to post-LIA climate shifts. A wet period ended LIA, followed by a two-step warming identified from different proxies and models. The pattern of change coincides with the known changes in climate. This suggests that after the LIA, changes in climate have been the driving force behind changes in peatland ecology and carbon sequestration in it. The results show that the way northern bogs respond to changes in climate can on the short term have huge effects for the vegetation, and on long term threaten the whole peatland and its carbon stocks.

These changes are manifested through changes in the relation of primary production to decomposition and local hydrology. Different microhabitats are more vulnerable to climate shifts than others. In future climate warming will continue to influence northern peatlands. Depending on the scale of change, peatlands can act as a sink of atmospheric carbon, or if a watershed is reached, release large amounts of carbon to the atmosphere. Most likely this would not only destroy peatlands in large quantities, but also further enhance the positive feedback between carbon release and peatland drying.

Avainsanat – Nyckelord – Keywords
carbon cycle, paleoecology, plant macrofossils, environmental change

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1. Introduction

Northern peatlands are a valuable, volatile carbon stock and hold 30 % global terrestrial organic carbon (Yu 2011). Peatlands are areas where due to high soil moisture, decomposition of organic material is slow, producing layers of peat, and biota is adapted to wet or semi-aquatic conditions. In geosciences peatlands are defined by the thickness of peat stratigraphy, while biosciences define peatlands according to peat forming plants (Korhonen & Vasander 1998). Climate is the most important control on peatland ecology (Charman et al. 2012). Peat, or partially decomposed vegetation, provides a valuable record of past climate change (Gorham 1991).

Different climatic periods of the last millennium are mostly affiliated with changes in external forcing, particularly solar forcing, which were followed by changes in atmospheric and oceanic circulation (Wanner et al. 2008; Helama et al. 2010; Diaz et al. 2011). Increasing temperatures, changes in precipitation patterns, deglaciation in all continents and what we still fail to recognize, create demand for more knowledge on the effects of climate warming (Overpeck et al. 1997; Frolking et al. 2011; Linderholm et al. 2018). As high latitudes face severe environmental change in the future, their response to rapidly altered ecology will determine the future for large carbon stocks and change carbon fluxes particularly in the high northern latitudes (Dise 2009; van Oldenborgh et al. 2014).

Paleoecological and paleoclimatic studies from peat stratigraphy have a long tradition. Long-term and large-scale climate-induced shifts in peatland hydrology during the Holocene, from 11 ka BP to present, are relatively well understood (Wanner et al. 2008; Linderholm et al. 2018). However, it is still unresolved how quickly the peatland vegetation may respond to changes in environmental conditions (Strack et al. 2004; Tuittila et al. 2013). This is a critical gap in understanding of peatland ecology and history of this habitat (Dise 2009; Yu 2012). In order to study how swift climatic change can affect peatlands, I examine in high-resolution past changes in a period known to have turbulent climatic conditions. I will examine bog vegetation response to known climate variations at the end Little Ice Age and during the following warming phases.

The dynamic relationship between peatland Net Primary Productivity (NPP), rate of decomposition, accumulation of organic matter and water table level determine the carbon budget of a peatland (Gorham 1991; Yu et al. 2009). All of this is controlled directly or indirectly

by climatic conditions. Previous studies point out that peatlands can develop a rapid response to water level drawdown (Strack et al. 2006; Charman et al. 2007). I used high-resolution paleoecological analyses quantifying ombrotrophic peatland response to post-LIA warming to understand the effect this might have on northern peatland carbon stocks. Several different proxies and dating methods are used together with statistical analysis tools to produce the most accurate image possible of the post-LIA development of northern bogs.

The key tools for this study were the high-resolution water table reconstructions, macrofossil analyses and age-depth models. These do not only indicate past climate development but also produce an image of carbon accumulation in this volatile part of the biosphere (Väliranta et al. 2007). Since such high-resolution studies on this period have not been produced before, two more traditional datasets produced in previous studies, were added from the same time frame (Tuittila et al. 2007; Väliranta et al. 2012). These give the study more scope both in terms of study area and in the effect of regional attributes to peatland response.

To best understand changes in vegetation, primary production and climate, study of several proxies should be applied. Micro- and macrofossils, age-depth curve, peat density and C/N ratio are important factors recognized in peatland records. Changes in hydrology, seasonality and temperature are preserved in vegetation and testate amoeba records, with little lag (Lamentowicz & Mitchell 2007; Amesbury et al. 2016).

This study is performed as a part of a larger study of boreal and arctic peatlands and their carbon dynamics. My research questions for this thesis are: 1) Can the known climate shifts after LIA be recognized in the northern peatland records, 2) What type of response did these shifts in climate cause in peatland ecology, and 3) How this has affected peatland carbon stocks?

2. Climate and the peatlands after deglaciation

Glaciation reached its peak in the northern hemisphere *circa* 21 ka BP, during a period named the Last Glacial Maximum (LGM). After LGM, the overall climatic trend has been towards a warmer world. However, this development has been far from stable. Several cold periods have intruded between periods of warm climate, and major changes in precipitation have often followed suite. The Younger Dryas, *circa* 12. 5-11.7 ka BP (Fairbanks 1989), was the most significant postglacial cooling period, which caused deglaciation not only to slow down, but locally also restarted glaciation. After roughly a thousand years of cooler conditions, climate

continued warming. Warm climatic conditions reached its peak in 8 to 6 ka BP, in a phase named the Holocene Thermal Maximum (HTM). This warmer phase allowed tree lines to reach far norther and higher than at present (Seppä et al. 2002). Long growing season, moist climate and well defined seasonality meant that climate was also optimal for peatland vegetation to thrive (Jones & Yu 2010).

The solar output is the most significant exogenous control on the planet's surface temperature and creates differences in air pressure, which control heat energy transfer across the planet (Bond et al. 2001). Changes in solar activity create variations into temperature on both land and sea, and affecting global air and oceanic circulation patterns. This in turn has affected climate, as heat and moisture transported by oceanic currents and global wind patterns weaken, strengthen or change direction (Wanner et al. 2008; Palastanga et al. 2011). LIA is associated with strong volcanic forcing and weak solar forcing, thought to have imposed conditions, where less solar energy could reach high northern latitudes. Cooler high latitudes were contrasted by drier and warmer low latitudes, as they received much of the heat that was previously transported toward polar regions. Periods of low numbers of sunspots, named Maunder minimum (1645-1715) and Dalton minimum (1790-1820) indicate lower solar activity and coincides with cooler climate of LIA (Eddy 1976; Bond et al. 2001).

2.1. Climate of the past millennia

Climate has considerably varied during the last millennium. The major climatic anomalies have been the Medieval Climate Anomaly (MCA), *circa* 1000-1580 and the Little Ice Age (LIA) *circa* 1580-1880 (Wanner et al. 2008; Mann et al. 2009; Ahmed et al. 2013; Linderholm et al. 2018). These climate periods were not globally congruent but are best recorded from the Northern Hemisphere archives (Nesje et al. 2008; Mann et al. 2009; Cronin et al. 2010; Cook et al. 2015). For instance, these phases have been identified from high-latitude peat archives as changes in past peatland vegetation (Väliranta et al. 2007; Charman et al. 2012; Mathijssen et al. 2016). Other sources for the past climate include past lake level data, drift ice records, dendrochronology and glacial deposits (Mann et al. 2009; Diaz et al. 2011).

MCA was a warm period extending from the beginning of the millennium to around 1580. The MCA witnessed human population extending further north and in greater numbers than before (Helama et al. 2010; Diaz et al. 2011; Hanhijärvi et al. 2013). LIA in turn is a period defined by

significantly colder, moist climate and higher water table, lasting from 1580 to 1880 (Hanhijärvi et al. 2013; Morris et al. 2015). In turn human population shrank and withdrew southwards in Northern Europe. These fluctuations in climate are thought to have been indirectly caused primarily by changes in solar forcing and to a lesser extent by volcanic forcing (Wanner et al. 2008; Mann et al. 2009).

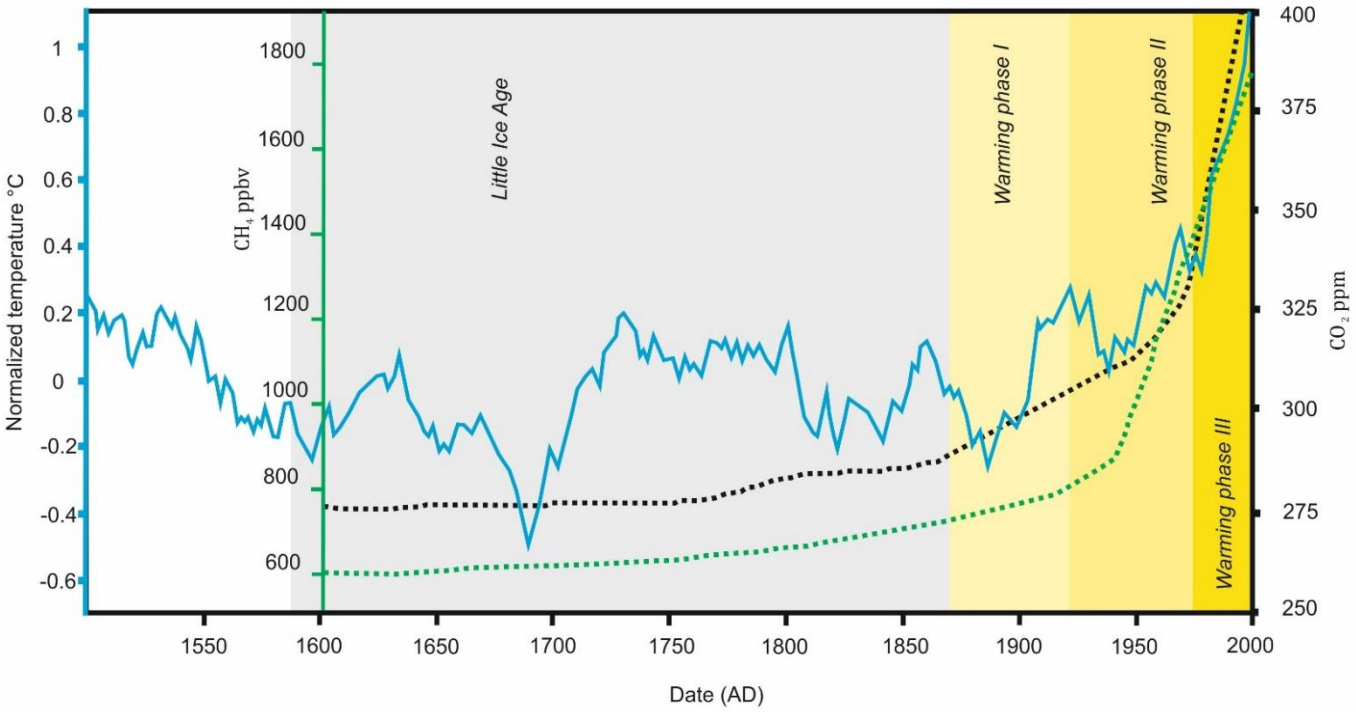

Figure 1. Normalized winter temperature anomalies (blue line) in Europe (Goosse et al. 2006). Black dashed line is CO_2 and green dashed line is for CH_4 (Overpeck et al. 1997). Little Ice Age (grey) is followed by three warming periods (light, bright and dark yellow). First two warming phases are viewed as the unraveling of cold climate forcing. Warming phase III is a product of human induced global warming.

Volcanic forcing is thought to have played a role in cooling the climate by increasing albedo of the atmosphere, thus reflecting solar energy back in to space. This hypothesis is based on the fact that volcanism is an input of several aerosols and gases into atmosphere, like sulphur, that are highly effective in reflecting solar radiation (Wanner et al. 2008) However, there are problems with this hypothesis. As volcanism is a source of so many aerosols and gases, some of them have the opposite effect on climate. Large amounts of different greenhouse gases are released through volcanism and warm the planet. Secondly, many aerosols, like sulphur, also have a short residence time in the atmosphere (Robock 2000). A large, continuous eruption or a steady series of eruptions would be required to maintain a powerful enough control on climate. Evidence for past eruptions during the last 500 years suggest a more episodic nature

of large eruptions (Crowley 2000). It is consequently thought that volcanic forcing has had only a secondary position in cooling the climate (Mann et al. 2009). Several strong tropical eruptions have cooled the climate at times, but that has already happened in a system in which solar forcing has been small (Wanner et al. 2008).

2.2. Warming

For the last 150 years, global climate has seen increasing temperatures, and the speed of change has been accelerating. The end of the latest postglacial cooling came to an end after the mid-19th century (Wanner et al. 2008). This was the beginning of the first warming phase. It marked the end of LIA, and can be seen as the weakening of those forcing controls, which for almost three centuries controlled the cooler climate (Linderholm et al. 2018). The cause of this warming is thought as a combination of rising solar forcing and decreased volcanic forcing and their feedbacks to climate (Mann 2009). The solar minimums ceded to modern solar maximum, period characterized by high solar activity and large number of sunspots (Bond et al. 2001). Volcanic forcing can also be seen weakened, as the number of large eruptions decreased (Crowley 2000). The first warming phase lasted until the 1930's. After this, a colder decade intruded in between. This began the second warming phase, in which warming initially had ceased, only to return after two decades. The 1930-40's was colder and it was not until the 1950's when the climate started warming again (Goosse et al. 2006). The two first warming phases were internally alternating between cooler and warmer years and global warming was much slower and steadier in comparison to what was to follow.

The third and latest phase of global warming that continues today started after the mid-21st century, around the 1960's and 70's (Goosse et al. 2006). This second warming phase is much more rapid in nature than the previous ones, and is thought to be influenced strongly by increases in greenhouse gases in lower atmosphere (Fig. 1) (Crowley 2000). Greenhouse gases are thought to have started accumulating already in the 1920's. However, only after the mid-20th century the levels of CO_2, CH_4 and others have grown exponentially. During this latests and still active warming phase, temperatures in lower atmosphere have reached higher than any time after Holocene Thermal Maximum (Overpeck et al. 1997). Global warming is advancing at a different pace in different regions. Arctic regions warm faster than lower latitudes (van Oldenborgh et al. 2014) and thus present an increasing burden on northern peatlands and to the carbon stored within them.

2.3. Northern peatlands

Northern peatlands make up of roughly 90 % of global peatlands and most lie within the boreal ecoclimatic zone (Fig 2). They exist in climatic conditions, where annual precipitation is between 200 mm to 1000 mm and annual mean temperature between 5°C and -12°C (Yu et al. 2009). Peatlands have an important, dynamic function in the global carbon cycle (Yu et al. 2010). Peatlands generally act as a sink of atmospheric CO_2 and as a source of CH_4. However, this trend has not remained consistent throughout their past.

Significant part of the earth's terrestrial carbon is stored in northern peatlands (Loisel et al. 2014). Total stock is estimated around 500 GtC ±20%, which is 90% of global peatland stocks and 30 % of global soil stocks (Yu 2011). Carbon is stored through accumulation of decaying organic material, and is released back to the atmosphere through metabolism of various micro-organisms and plant respiration (Korhonen & Vasander 1998; Laine et al. 2009). What remains of the net primary production after leaching and disturbances, is stored as peat. Depending on the climatic conditions, peat may be stored for thousands of years. Peat stratigraphy holds within itself a valuable archive of past environmental changes (Gorham 1991).

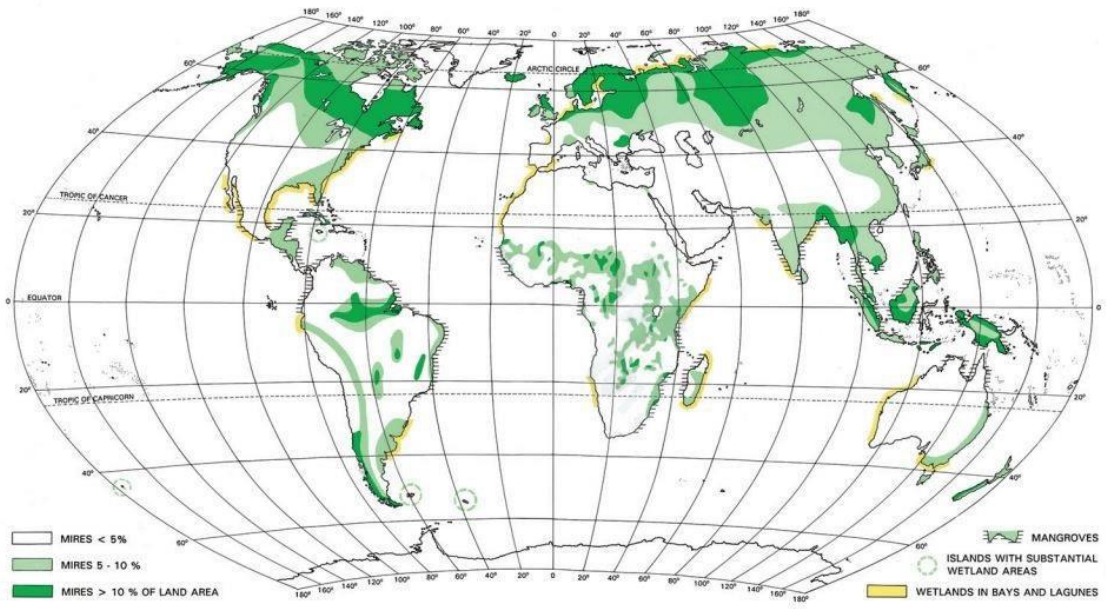

Figure 2. Majority of global peatlands are located in the high northern latitudes (Strack 2008).

2.4. Peatland ecology

Peatlands are complex systems which dynamics are controlled by several autogenic and allogenic forcing factors and recognizing a clear signal of a particular factor, or a set of factors is difficult (Yu 2012; Charman et al. 2012). Depending on the scale of study, different factors control bog vegetation and carbon sequestration. In microtopographic and –ecological scale; competition and water table level have great roles. As the scale of study increases, other local factors come into effect, such as land use and topography (Rydin et al. 2006; Tahvanainen 2011). However, in larger scale, climate is overall the most important factor controlling peatland vegetation and carbon sequestration (Fig. 4). Climate is a high hierarchy factor, that controls directly or indirectly lower hierarchy factors, such as hydrology and vegetation, that are important in local scale study (Yu et al. 2009). Other allogenic factors are for example fires and human activities (Tuittila et al. 2007).

Hydrology is regulated by climate and peatland succession, i.e. growth in peat thickness. Peatland vegetation varies depending on water table levels and the peatlands age (Laine et al. 2009). Peatland ecological succession makes time an important factor in controlling peatland vegetation (Gorham 1991). As peatland ages, it typically develops an increasingly thickening peat stratigraphy. This slowly alters the local hydrological conditions. Surface flow from the peatland basin controls the hydrology of a shallow, typically young, fen type minerotrophic peatland. As time progresses, the thickening peat layer separates the peat from water flowing from the basin. Such a peatland gains virtually all of its water from rainfall, thus named ombrotrophic (Korhonen & Vasander 1998).

Bogs have a distinct microtopographic pattern that becomes more prevalent as the peatland ages (Rydin et al. 2006). The surface is a mosaic of wet hollows and dry hummocks. Between these lies the middle ground, lawn, which can be further divided into higher and lower parts (Korhonen & Vasander 1998). Even small variations in topography are important, as a rise or plummet in surface means a drier or a more wet microhabitat, respectively (Karofeld 1998). Hummocks lie 20-35 cm above the water table throughout the year, and there are found the most dry-resisting bryophytes and some vascular plants. Hollows and small lakes are constantly or seasonally under the water level, leaving room only for semi-aquatic species (Laine et al. 2009).

The succession from minerotrophic to ombrotrophic is called ombrotrofication (Klinger 1996). In this process, less and less nutrients from surface flow reach the peatland making bogs barren, nutrient poor environments where only a handful of species survive. Bogs have low electrolyte and calcium levels compared to fens (Rydin et al. 2006). These bog type peatlands are dominated by bryophytes, or moss. Genus *Sphagnum* is the most important (Laine et al. 2009). In nature, ombrotrophication usually requires hundreds or even thousands of years to take place, unless peatland ecology is greatly disturbed (Granath, et al. 2010; Väliranta et al. 2017). For example, a rapid drying can set succession in motion in a much faster timescale, even in the span of decades (Hughes & Barber 2003; Tahvanainen 2011)**.**

2.5. Bog vegetation

Sphagnum are a successful and a diverse genus and tend to cover peatlands from shore to shore. They are efficient in utilizing nutrients and survive in barren environments. Adaptive, wide spread, hard to break down and fast growth allows *Sphagnum* to sequester large amounts of carbon. It includes highly specialized species that survive in different ecohydrological niches, where water level, shading and pH varies (Fig. 3) (Laine et al. 2009). Ecohydrology refers to both water level and its chemical qualities. As the primary autotroph of bog type peatlands, *Sphagnum* spread quickly if any wet environments are available. *Sphagnum* are able to alter their surroundings to their own advantage in a process termed paludification. This happens by waterlogging and acidifying soil to levels intolerable to most other plants (Crawford 2003). *Sphagnum* produce organic acids that lower the surrounding soil pH. Bog type peatlands tend to be acidic, with a pH less than 4 (Rydin et al. 2006).

Sphagnum are grazed only by one species of enchytraeid worm named *Cognettia sphagnetorum,* and are highly resistant to decay (Laine et al. 2009). While growing fast they accumulate carbon from the atmosphere and once deceased they are slow to let carbon release back into circulation (Roulet et al. 2007). Their success as a genus has partly made bog type peatlands such an important component in the carbon cycle (Rydin et al. 2006).

Marchantiophyta, or liverworts, often live amongst the dominating *Sphagnum*, but are far less resistant to decomposition and leave little or no signs in the peatland record (Rydin et al. 2006). Concerning the area of this study, the most notable liverwort is *Mylia anomala,* which is often found growing among *S. fuscum* branches. *E. vaginatum* has similar attributes as *Sphagnum*, it

is highly resistant to decay further increasing accumulation rates (Laine et al. 2009). *E. vaginatum* acts as an important ecosystem-engineer in ombrotrofication too (Hughes and Dumayne-Peaty 2002; Väliranta et al. 2017)**.** *E. vaginatum* prefers to grow in lawns, where its long roots can reach the water table even in dry periods, but is at the same time safe, should too wet conditions prevail (Hughes et al. 2000; Tuittila et al. 2007).

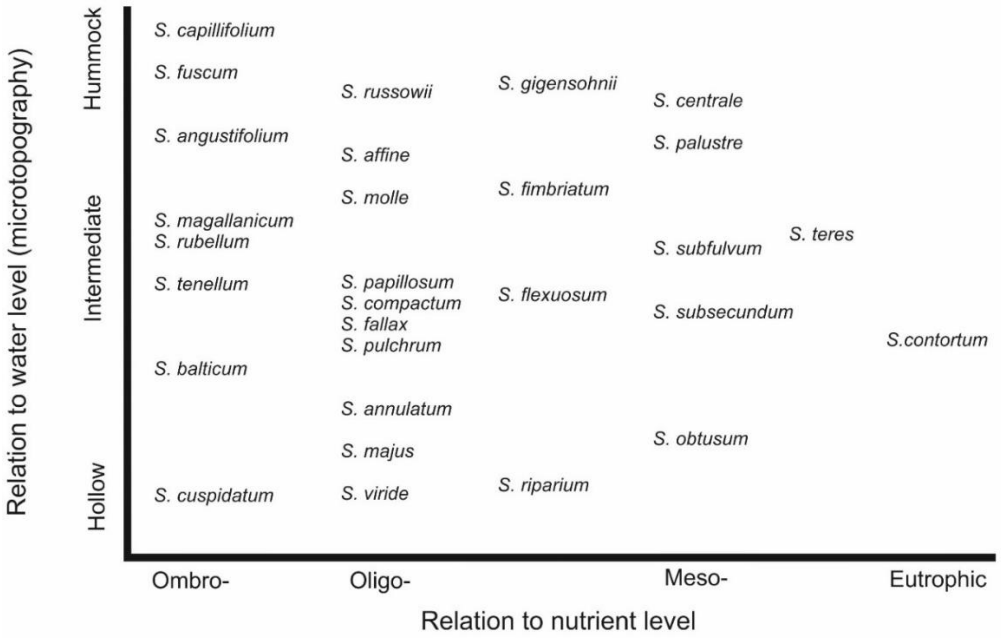

Figure 3. Eastern Fennoscandia *Sphagnum* niches in relation to water and nutrient levels (Laine et al. 2009, modified). Other factors, such as shading, pH and competition have an effect on *Sphagnum* growth.

In an acidic environment, where nutrients are hard to come by, only few vascular plants have managed to utilize what little nutrients there are. Wet, seasonal conditions also favor a narrow group of vascular plants like, forbs, sedges, shrubs, and small trees (Tuittila et al. 2013). In acidic conditions, Phosphorus is dissolved more readily, and this is utilized by *Eriophorum vaginatum* (Hughes et al. 2000). Vascular plants are typically found in greater numbers in younger and less developed peatlands. Sedge genus *Carex* are an exception, they are dominant in fens and often found in wet microhabitats in bogs as well (Korhonen & Vasander 1998).

In cool conditions where little vegetation is yearly produced, and decomposition is slow, resulting peat is high in density peat is usually dark brown, since it has had time to highly decompose in aerobic conditions. In a warm temperature scenario, with distinct seasonality, new organic material is produced rapidly. Layers formed in such a period are low in density. Such peat has not had much time to decompose in aerobic conditions and is often lightly colored brown and possibly with shades of red and green.

2.6. Peatlands in the carbon cycle

Peatlands form a unique carbon stock, where large quantities of organic carbon is stored in terrestrial environment close to the atmosphere. Carbon fluxes in peatlands take place almost entirely through the atmosphere (Frolking & Roulet 2007). This one of a kind interaction makes peatlands able to store large amounts of carbon from the atmosphere, but leaves carbon stocks vulnerable to environmental changes (Dise 2009; Charman et al. 2012; Morris et al. 2015). Carbon is stored into peatlands trough photosynthesis. Plants eventually die and ecosystem NPP is transferred from living ecosystem to soil yearly as growing season ends. The decomposition in peatlands is slow and incomplete, and stores plant fragments for thousands of years, forming soil that is high in organic carbon (Rydin et al. 2006).

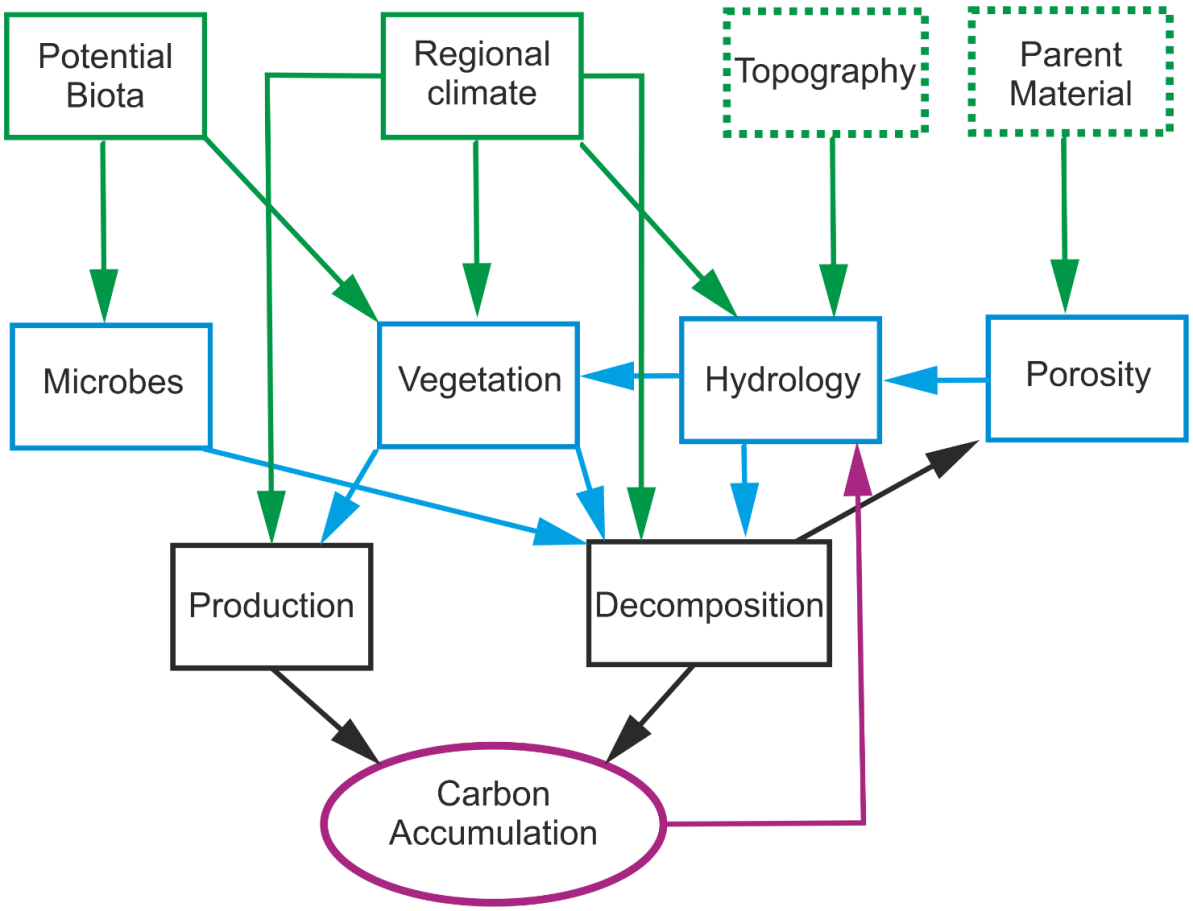

Figure 4. Flowchart of controls over carbon accumulation in northern peatlands. State factors are colored in green, intermediate processes in blue and direct controls in black. Dashed boxes indicate, that these factors are most relevant in the early development of peatlands. Arrows are colored according to the origin of control (Yu et al. 2009, modified).

Water table level defines the line between anaerobic and aerobic decomposition and thus hydrology has a great control on the carbon flow in peatlands (Frolking et al. 2010). Decomposition happens slowly in anaerobic conditions below the water table in catotelm, but above the water table, in the narrow acrotelm, aerobic decomposition takes place at a faster rate. (Gorham 1991). Due to seasonal changes in water table level, the border between acrotelm and catotelm is more a transitional zone than a distinct boundary. Decomposition is carried out by various micro-organisms, which produce CH_4 in anaerobic and CO_2 in aerobic conditions. It is through these gases that peatlands release most of their carbon. Small amounts are also released through dissolving carbon to surface waters and to groundwater (Roulet et al. 2007). Ecological disturbances*, i.e.* fires, anthropogenic land use change also hold a huge potential as great carbon sources that are also indirectly affected by climate. (Minkkinen et al. 1999; Turunen et al. 2002; Borren et al. 2004; Morris et al. 2015).

2.7. Climate and the peatlands

Climate is the most significant factor in controlling peatland C-stocks. As peatlands can survive in a relatively large climatic window, there are climatic conditions where carbon sequestration is higher, lower and even others where peatlands act for a period as a source of carbon, not a stock (Yu et al. 2010). A moist and a warm climate, with distinct summer-winter seasonality is the optimal climatic frame for carbon sequestration. Peatlands occur in areas, where relative humidity (RH) is above 65 %, annual precipitation is between 200 mm to 1000 mm and annual mean temperature between 5°C and -12°C (Yu et al. 2009). As climate shifts towards cooler and dryer conditions, with less clear seasonality, less carbon is stored in peat (Charman et al. 2012).

Photosynthetically Active Radiation (PAR) and length of the growing season are the most important climatic variables for carbon sequestration. Photosynthesis, measured as primary production, is in the end what causes carbon intake from atmosphere. Summer temperatures and solar energy control primary production, as photosynthesis in bryophytes is possible only in temperatures above 0°C with energy from solar radiation (Charman et al. 2012). Conditions outside the growing season have little bearing on carbon stocks, as in winter time, carbon is neither released nor added to the system in significant quantities (Yu et al. 2003).

Hydrology is an important factor in bog ecology and carbon flux. Water balance allows peatland to exist if evapotranspiration and runoff are small enough compared to precipitation. High RH

peatlands actually occur in areas where annual rainfall is low, but evapotranspiration is also low, with mean annual temperature typically -10°C. These are in the coldest parts of peatland distribution. Drier peatlands exist in warmer conditions, where typically rainfall and surface flow can barely match high rates of evapotranspiration (Yu et al. 2009). Studies show that local hydrology's importance is limited to a threshold. When local hydrology is producing enough soil moisture to sustain peatland vegetation, its significance reduces sharply (Yu et al. 2003). However, when critically low values of water table are reached, soil becomes vulnerable to drying and peatland vegetation will disappear in face of vascular plants, such as shrubs (*Betula nana, Pinus sylvestris*), which are better adapted to drier conditions (Strack et al. 2004).

Drying also leaves peatlands more vulnerable to fires (Turetsky et al. 2011). However, a forest fire needs to be extensive in magnitude to have a long-term effect on a peatland (Sillasoo et al. 2011). Thus, likelihood of carbon releasing to atmosphere increases as the water table decreases beyond a certain threshold. Hydrology is a necessity in sustaining a peatland. Abrupt changes in bog vegetation can also happen without a sudden change in climate. A long period of increased surface wetness may cause a positive feedback, where decreased decay rates and increased porosity of peat leaves the peatland surface vulnerable to drying (Charman 2007). Drier peatlands emit larger quantities of CO^2 (Strack et al. 2006).

Time is also an important factor, as the peatlands capability to store carbon increases with its phase in ecological succession. Ombrotrophication, the process of peatland drying caused by growth in thickness of the peat column or local drying, is an important factor of this ecological succession (Rydin et al. 2006). During this transition, hydrology and local factors typically diminish in importance and the significance of climate over other factors increases over time. More developed peatlands are transformed into bogs (Korhonen & Vasander 1998). This means transition from fen type minerotrophic, or basin controlled hydrology, to bog type ombrotrophic, or climate controlled hydrology (Gorham 1991).

Peatlands effect the climate itself through a negative and a positive feedback. Peatlands remove CO_2 from atmosphere and this process strengthens when CO_2 levels rise. CO_2 is an important greenhouse gas and climbing CO_2 levels are associated with rising temperatures and increased primary production. This means that as CO_2 levels and temperatures rise, peatland vegetation respiration increases, taking in more CO_2 and stores it into slowly decaying organic carbon stock (MacDonald et al. 2006; Frolking & Roulet 2007; Dorrepaal et al. 2009).

2.8. Peatlands in the past millennia

Since the LGM, peatlands have mainly acted as a climate cooling component. Modern peatlands act as sink of CO_2 and have overall a cooling effect on climate. However, during the early Holocene peatlands produced much more CH_4 into atmosphere and peatlands had an overall warming effect on climate. (Frolking & Roulet 2007; Korhola et al. 2010). Moisture was available in large quantities in the periglacial environment due to melting glaciers. Higher methane emissions were caused by the relatively high water tables in the young peatlands. Atmosphere at that time had very low levels of any greenhouse gases, thus the methane produced by these early peatlands was particularly effective in warming the climate (Smith et al. 2004; MacDonald et al. 2006). It was only during the Holocene Thermal Maximum that this trend started reversing, around 8 ka BP, and northern peatlands became a cooling factor in the climate (Wanner et al. 2008).

Variations in climate can have significant impact on these large terrestrial carbon stocks. One critical fact behind this is, that 70% of modern northern peatland carbon had already stored before 4 ka BP, when the Holocene Thermal Maximum had passed (Yu 2012). Presently, a significant proportion of this carbon in the arctic is controlled by permafrost. Only little carbon can be stored or released during the short growing season. This “deep frozen” organic carbon is sensitive to rising temperatures and growing summer precipitation (Kuhry et al. 2010; Frolking et al. 2011; Schuur et al. 2013). Altering climatic conditions might release major part of this stock into the carbon cycle (Dise 2009). The impact of such change depends largely on local climatic and hydrology factors that control whether vegetation can assimilate carbon as quickly as it is released through decomposition. However, it is important to understand that permafrost brings a set of new factors into the system and such peatlands may react differently to boreal peatlands (Dorrepaal et al. 2009).

The effect of climate on peatlands is visible within peat stratigraphy across the boreal ecoclimatic zone. In northern peatlands MCA was characterized by seasonality, wet winters and dry summers, high temperatures and rates of evaporation leading to a lower water table (Linderholm et al. 2018). The MCA also experienced internal variations, but the overall effect favored peatland growth more than the following LIA. These conditions generated high net primary production which over time led to high accumulation rates of organic carbon (Malmer & Wallen 2004; Charman et al. 2012). LIA in turn decreased temperatures and the rate of evaporation, leading to higher water tables, shorter growing seasons and ultimately to smaller

carbon accumulation (Helama et al. 2010; Diaz et al. 2011; Hanhijärvi et al. 2013; Linderholm et al. 2018). Climate warming after LIA has again turned conditions favorable for peatland growth (Charman et al. 2012). Increased temperatures have been linked to higher ecosystem respiration, stimulating autotrophic and heterotrophic respiration equally (Dorrepaal et al. 2009). Studies focusing on this latest period in peatland development are few in number and no high-resolution data has been unavailable until now.

3. Materials and methods

Peat accumulation is controlled by the balance of production and decomposition. To best understand the differences in vegetation, primary production and therefore climate, study of several proxies should be applied. Production changes can be visible in micro- and macrofossils, age-depth curve and in the density and C/N ratio of peat itself. This study is a part of a larger research project and some data presented in this study is supplementary material. Männikjärve and Kontolanrahka data (Väliranta et al. 2012), Lakkasuo data (Tuittila et al. 2007) and modern vegetation and testate amoebas by PhD students Nicola Kokkonen and Hui Zhang, respectively.

3.1. Study site

The study sites are three bogs in southern Finland, Lakkasuo (61°48’ N, 24°19’ E), Siikaneva (61°50’ N, 24°10’ E), Kontolanrahka (60°47′ N, 22°47′ E) and Männikjärve (58°52’ N, 26°15’E) bog in eastern Estonia (Fig. 5). All bogs are within the boreal ecoclimatic zone and their growing seasons lasts generally from May to October in Finland and from April to October in Estonia. Southern Finland, as well as Estonia, are and have been thoroughly populated and cultivated for thousands of years, and agriculture and forestry have affected each bog. Coring points in this study were selected from pristine parts in bogs, where anthropogenic activity could be removed as a factor. Areas with recorded draining or marks of human activity were avoided. Field studies for Lakkasuo and Siikaneva were carried out in October 2016. Männikjärve was studied in 2004 and Kontolanrahka in studied 2003, and the data was provided for this thesis in 2018.

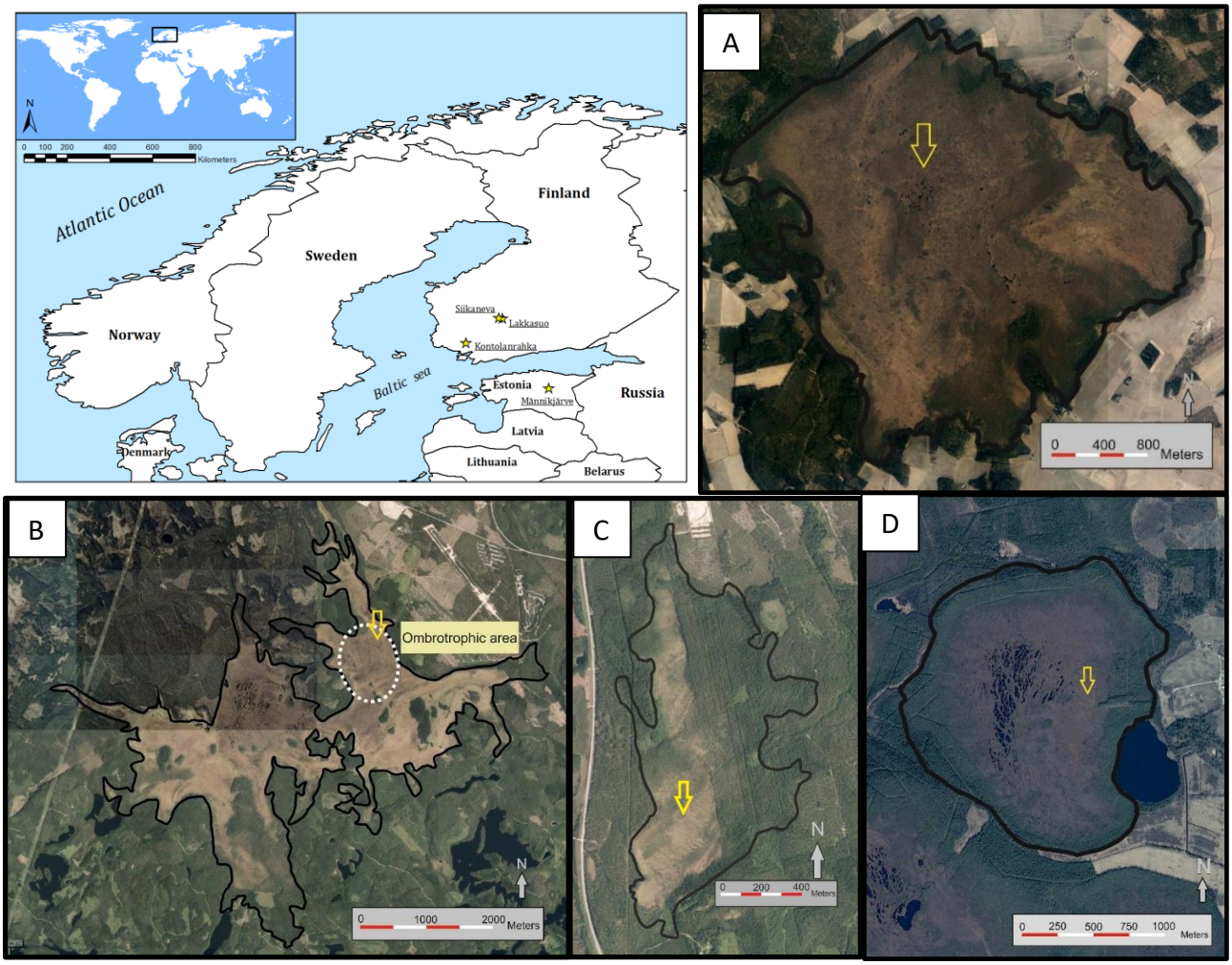

Figure 5. Study sites shown in a map of northern Europe A is Kontolanrahka, B is Siikaneva, C is Lakkasuo and D is Männikjärve. Yellow stars mark the peatlands and yellow arrows mark the coring points. Peatland limits have been roughly sketched in black. In Siikaneva, ombrotrophic area has been marked with a white dashed line, since major part composes of fen type peatland.

Siikaneva peatland complex (61°50' N; 24°10' E) is located in Ruovesi municipality, Pirkanmaa, Southern Finland, 170 meters above sea level. It is an open peatland with both fen and bog areas. The peatland is located within the bog-dominated Southern Finland, far south from the fen-bog transition line (Väliranta et al. 2017). Total area is *circa* 12 km^2 and major part consists of oligotrophic fens. This makes such a large peatland an anomaly in the bog dominated Southern Finland. Siikaneva is complex in shape, having three distinct branches in roughly north-south direction and one in east-west direction. Surrounding areas are primarily northern boreal forests and some agricultural lands. Peat thickness varies from 2 m to 6 m. Oldest basal peat ages in Siikaneva are over 10 ka cal. BP. The ombrotrophic part, where the study is conducted is a little younger, having started peatland initiation *circa* 9000 cal. BP (Mathijssen et al. 2016). Mean annual precipitation *circa* 700 mm and GDD is 170 days. Mean annual

temperature is 3.1 °C, mean July 15.3 °C and mean January -8.9 °C (1960-1990) (Ilmatieteen laitos).

Bog areas have a clear microtopographical pattern consisting of hummocks, lawns and hollows. Bryophyte vegetation is made up of *Sphagnum fuscum* and *Sphagnum rubellum* in hummocks, *S. rubellum* and *Sphagnum magellanicum* in lawns and hollows with *Sphagnum cuspidatum* and *Sphagnum majus* as dominant species. Vascular plants in bogs are *Andromeda polifolia*, *Calluna vulgaris* and *Empetrum nigrum* in hummocks, *Eriophorum vaginatum* in dry lawns but also in lower part of hummocks and *Rhynchospora alba*, *Carex limosa*, *Scheuchzeria palustris* in hollows. Fens have a monotonous lawn topography with *Sphagnum balticum*, *Sphagnum papillosum* and *S. majus.* Vascular plants in fens consist of *E. vaginatum* and several *Carex* species (Mathijssen et al. 2016). My results from field studies are in line with this description of plant composition.

Lakkasuo peatland (61°48' N, 24°19' E) is located in Ruovesi municipality, Pirkanmaa, Southern Finland. Total area is 1.2 km^2 and lies 150 m above sea level. Annual precipitation is *circa* 700 mm and GDD is 170 days (Ilmatieteen laitos). Mean annual temperature 3.1 °C, mean July 15.3 °C and mean January -8.9 °C (1960-1990). The bog is roughly rectangular in shape, longer in north-south axis and narrower in west-east axis. *S. fuscum, S. rubellum, E. vaginatum* and *Ericaceous* and *Pinus* commonly inhabit dry surfaces (Tuittila et al. 2007). My own field studies agree with these, and further recognizing *A. polifolia* and *S. balticum* as frequently appearing species. Peatland initiation in Lakkasuo began *circa* 9000 cal. BP, although margins of the bog only date as far back as 3000 to 5000 cal. BP. The eastern half of the peatland was drained for forestry in 1961, but unaffected the studied site (Minkkinen et al. 1999). In 2001 water level drawdown was also carried out, but the study site had been monitored since 2000, thus covering possible alterations in water level due to anthropogenic influence.

Männikjärve (58°52' N, 26°15' E) in Tooma municipality, Jõgevamaa, Estonia is a raised bog that belongs to the Endla mire system, part of East-Baltic Bog Province. The bog has a clear hummock-hollow topography with several large water pools in the middle and forested margins. Maximum peat depth is 7.5 meters. Bog lies 89 m above sea level, is circular in shape and total area is *circa* 3.2 km^2 (Karofeld 1998). Annual precipitation is 668 mm and temperature mean 4.5 °C. Snow cover last from mid-December to the beginning of April. Growing season last from April to October. Surrounding area is widely cultivated, apart from the mire systems. Several hiking trails have been cleared into the area. Vegetation in hollows is

dominated by *Sphagnum*, particularly by *S. palustris, S. magellanicum, S. balticum, S. majus* and *S. cuspidatum,* but also *R. alba.* Hummocks are habited by *P. sylvestris, B. nana, C. vulgaris, E. nigrum, Ledum palustre, S. fuscum, S. rubellum* and lichens, *Cladonia* and *Cladina spp*. Other vascular plants in the bog include *A. polifolia, S. palustris, R. alba, Drosera anglica* and *V. oxycoccus* (Karofeld 1998; Sillasoo et al. 2007).

Kontolanrahka peatland (60°47′N, 22°47′E) is situated in Pöytyä municipality, Southwestern Finland. The peatland is located 90 m above sea level. The peatland is surrounded by flat agricultural lands with clay soils. Kontolanrahka is a true raised bog, with dimensions 3.8 km x 3.8 km, equaling to *circa* 8.8 km^2 in area. Minor draining in the lag area has been committed for forestry and agriculture, but the center is in pristine condition. Mean annual temperature is 5 °C, GDD is 180 days and mean annual precipitation roughly 700 mm. Relatively low hummocks, numerous open pools and hollows are wide and wet (Väliranta et al. 2007). Center of the bog is more than 6 m above the margins. Maximum depth is 7.1 m and central dome generally exceeds 5 m in depth (Väliranta et al. 2012). The bog started forming around 9400 cal. yr. BP. Hummock vegetation in Kontolanrahka consists of *P. sylvestris, B. nana, C. vulgaris, E. nigrum, S. fuscum* and *S. capillifolium*. *R. alba*, *S. palustris*, *S. balticum, S. majus* and *S. cuspidatum* form major part of hollow species (Väliranta et al. 2007).

3.2. Peat and macrofossil analysis

Männikjärve, Kontolanrahka, and Lakkasuo samples were collected 2006, 2003 and 2001-2002, respectively. Three 60-cm long surface peat cores were collected from Siikaneva bog in October 2016 using a box corer. GPS was used to save the coordinates of the exact study sites. The samples form a transect representing three different microhabitats; low lawn, high lawn and low hummock. These microhabitats were chosen since they depict most accurately changes in bog vegetation. Current plant communities were surveyed at coring points and water table level was measured from the produced opening in peat.

Figure 6. Cores were wrapped in plastic on site. Frozen, cut in to 1 cm thick subsamples, labelled and some dried, while others refrigerated, all with maximum caution to avoid any contamination. Picture on the right demonstrates, how easy it is for the samples to be contaminated. © Joonas Alanko

The cores were transported from study sight to university premises and frozen. The frozen peat cores were measured and visual checks were made for any contaminating material that had moved to or attached to the core surfaces. All such material was carefully removed. The cores were then cut into 1 cm subsamples in laboratory conditions, rinsing all equipment after every cut, to limit contamination as much as possible (Fig. 6). Outer rims of subsamples were cut off and discarded. Subsamples were rinsed carefully with distilled water and stored individually in labelled plastic bags to avoid contamination. Subsamples for macrofossil analysis were afterwards stored in refrigerators to wait further analysis. A percentage of subsamples were extracted for C/N analysis and dating. In order to remove the moisture, subsamples were freeze-dried. Dried subsamples were ground to fine dust manually using mortars and stored in 5 ml jars.

The peat cores were analyzed in high-resolution (1 cm intervals) for bulk density. Bulk density was analyzed by measuring 5 ml of peat from every subsample, this was subsequently dried and weighed and thus bulk density could be calculated, using the formula $\rho_b = M_s/V_t$, where ρ_b is dry bulk density, M_s is mass of soil and V_t is total volume. C/N ratio was analyzed in 4 cm intervals. C/N analysis was carried out by the author using a Micro Cube Elemental Vario CNS-analyzer in the laboratory of department of geosciences and geography, University of Helsinki.

C/N ratio is a proxy of past plant communities, in peatlands *Sphagnum* peat has high C/N compared to *Carex* peat. Nitrogen is usually the limiting factor for terrestrial plants and serves as reference of growing conditions and in different growing conditions plants vary their carbon storage. Ratio between C and N points to how able plants were to live in past circumstances.

The co-working project provided data on water levels in study sites. Water levels were monitored weekly during the growing season trough water wells. One meter long, 2 cm in diameter PVC pipes were used as rudimentary wells. Perforated in every 5 cm, and the bottom sealed, the pipes were installed in spring, after thawing of the moss. CO_2 and CH_4 flux measurements were done with chambers on 60 cm x 60 cm plot sites and have been continuing since 2000 on Lakkasuo. Water table level is measured as the distance the water surface lies from the peat surface in centimeters. Vegetation was monitored using a 60 cm x 60 cm frame for plotting a site. The projection of cover was estimated for each taxon by two researchers in order to reduce bias. For calibration, the results were regularly compared to sample images. Due to different layers of vegetation, the sum of cover can be over 100%.

Accumulated and incompletely decayed organic material consists of microfossils, *i.e.* pollen, and macrofossils, the remains of contemporary plants which represent local habitat conditions. Macrofossils are less likely to be carried away due to their larger size and mass, and are a more reliable *in-situ* proxy than microfossils. These proxies can be used to reconstruct past environmental and climate changes. Differences in past vegetation assemblages reflect past environmental conditions (Barber et al. 2003; Tuittila et al. 2013). Plant macrofossil analysis followed procedure described in Väliranta et al. (2007). A core from each microtopographic environment was selected from Siikaneva for visual analysis. For the macrofossil analysis, the peat cores were cut into 1 cm subsamples. A 5 cm^3 piece was randomly extracted and cleaned under running water using a 140-µm sieve. 1 cm resolution on low hummock core from Siikaneva and 2 cm resolution on the rest two cores (high and low lawn) were analyzed. A stereomicroscope was used for identification and a high-power microscope was used for species-specific identification (Fig. 9). In total 103 subsamples were analyzed visually.

Testate amoeba community composition was analyzed by PhD student Hui Zhang. This analysis was performed in order to gain a second proxy source of paleohydrological data to compare with my findings in plant composition. Testate amoeba are commonly used to reconstruct changes in past peatland surface moisture conditions (Lamentowicz & Mitchell 2007).

Microscopic animals, such as testate amoeba, have virtually no lag in their proxy signal. In bog conditions, their ecological niches are primarily determined by water table level and thus are highly applicable for this study.

3.3. Chronologies

In order to link past changes in plant composition to climate the cores were dated by two different methods, ^{210}Pb and ^{14}C-dating. I wished to minimize the margin of error produced by any single dating method and thus I apply two different radioactive elements. ^{210}Pb-dating is applicable for most my samples, but it cannot produce accurate dates for the oldest depositions in my peat data. Margin of error in ^{210}Pb-dating increases to unacceptable numbers as the age of the sample exceeds 200 years. Therefore, bottoms of every analyzed core were dated using ^{14}C-dating, which in are turn accurate enough only for samples *circa* 300 years in age.

Radiocarbon dating is based on radioactive isotope ^{14}C. It is produced in the upper atmosphere by means of neutron bombardment of nitrogen atoms. However, the ^{14}C-levels in the atmosphere cannot be assumed as constant, thus different models and calibrations are needed to ensure accurate results. Radiocarbon is oxidized into CO_2, and it is in this compound, that it enters into organisms. Primarily ^{14}C is taken in to plants in respiration, and further carried up the food chain to heterotrophs. Radioactive carbon is transferred to autotrophs in photosynthesis and through predation into heterotrophs as well. As a lifeform dies, it ceases to accumulate ^{14}C and it starts to break down from an assumed constant level with a half-life of 5700 years. Siikaneva on each core ^{14}C-dating was carried out for the bottom subsamples in December 2017 in the Poznan Radiocarbon Laboratory, Poland. Carbon dating methods have been proven efficient in measuring radiometric ages between 300 to 50 000 years in age, including peat stratigraphy (Bradley 2014). It is thus a suitable choice to date core bottoms for this research. Combined dating methods allow an accurate age-depth analysis, producing a model, portraying development of peat accumulation.

Lead ^{210}Pb analyses were carried out by the author in University of Exeter, United Kingdom, June 2017. This relatively novel dating method was chosen due to the increasing use, study and improvement of this analysis. ^{210}Pb-dating is well suited for this analysis since it covers dates from recent to *circa* 200 years and is ideal for highly organic content, such as recent peat deposits. For every sample above and including 40 cm in depth. Dating analyses were

performed on two cores that represent high lawn and low hummock microtopographies from Siikaneva. The dating was carried out by the author. The dating analysis was performed according to method described by Nicola Sanders (2013). The analysis is based on the radioactive isotope ^{210}Pb, which occurs everywhere in nature. ^{210}Pb is formed as a decay product high in the atmosphere. The decay chain consists of: ^{238}U, ^{226}RN and ^{222}Rn and after ^{210}Pb: ^{210}Bi, ^{210}Po and the end product is ^{206}Pb *i.e.* stable lead. ^{210}Pb is absorbed in to all biota after it is deposited trough precipitation down on to earth's surface from the atmosphere.

The analysis was performed under strict health and safety measures. 0.5 grams of the freeze-dried and grinded peat subsamples were placed in acid washed beakers. Then 1 ml of radioactive ^{209}Polounium spike was added. The subsamples spiked with radioactive polonium spikes the original signal from ^{210}Pb. Samples were bathed in acid several times and the excess liquid boiled away in order to have samples enriched with the wanted radioactive isotope in the following order.

10 ml of HNO_3 (nitric acid) was added to beakers. The mixture was then heated to 80-90 °C on a hotplate in order to set the sample boiling. Constantly mixing and monitoring the boiling samples, dried ones were removed to cool before material would burn. 10 ml of 30% H_2O_2 (hydrogen peroxide) was added to cooled samples and again brought to boiling in the same temperature and constantly mixing and monitoring. After drying and cooling this was once more repeated with 5 ml of 6M HCL (hydrogen chloride) and set to cool. Then what was remaining of the peat samples were dissolved into 5 ml of HCL. The beakers were rinsed with 0.5 ml of HCL in order to transfer the solution into test tubes. These were centrifuged in 2500 rpm for 10 min to separate any solid material left.

The radioactive solution was then placed in acid washed glass plating jars with a magnetic stirrer. The α-radiation from the solution was absorbed into one side of a silver planchet. The concave sides of planchets were painted in order to confine the absorption of radiation in one side and a hole was punched through the planchet for suspending. Using fishing line, the planchets were suspended in the jars. 0.2 g of ascorbic acid was added. With the lid on, the radioactive jars were set to mix on magnetic stirring tables for 24 hours to absorb as much radiation as possible. After the stirring, the planchets were rinsed with DI water and placed in alfacounters for three days (Sanderson 2013).

3.4. Models

Age-depth models were produced in order to have a clear image of the carbon accumulation in the studied bogs. A hypothetical, perfectly linear age-depth curve would mean a stable peat accumulation and any anomalies would show as changes in the slope. Slope should stay positive, unless material has disappeared from stratigraphy, which could happen due to fires and/or drying. A high slope in the age-depth curve implies rapid accumulation *i.e.* high carbon accumulation. This would imply favorable climatic conditions to *Sphagnum* growth and therefore carbon accumulation, *i.e.* warm, humid and distinctly seasonal climate. Low slope on the other hand suggests harsh conditions for *Sphagnum* and carbon accumulation, cold and too dry with less distinct seasons. From Siikaneva samples two age-depth models were produced from HL and LH cores each using the ^{210}Pb data. The age-depth models were produced using the R-program with R package Bacon v.2.3.3 (Blaauw & Christen 2011).

The samples included material younger than 0 cal. yr. BP, or material produced after 1950. This is known as "postbomb" material as it includes relatively high levels of radioactive material that originates from the high amounts of nuclear weapon tests conducted after the turn of the century. Siikaneva models were produced with the following parameters. The cores included data from NHZ1, or Northern Hemisphere Zone 1 of ^{14}C activity levels. All subsamples were older than -66 cal. BP and the section thickness was set as 0.4. Thickness is a parameter used to vary the flexibility of the model. The scripts used can be found in the appendix A.

Water table reconstructions were made in order to have a model-based understanding of the development of local hydrology and thus climate in the study area. Models were built using R-program with R package Rioja 15.1 (Juggins 2017). In ombrotrophic conditions WT is controlled by climate and therefore I chose to use WT reconstructions as the basis for climate shifts in peatland history. These reconstructions could then be compared to other proxies, to have a more complete understanding of peatland response to climate warming. In Siikaneva two reconstructions were produced, one produced from Lakkasuo and one for Männikjärve and Kontolanrahka each were available from previous studies (Väliranta et al. 2012). Water table reconstructions were performed using modern vegetation, macrofossil and water table data in R-program. A training set was created by using modern Lakkasuo vegetation as a proxy of water table level. A training set is a collection of data, functioning as examples on how to fit various parameters. In this training set, parameters are different plant taxa relation to water table. Other training sets were tested using data from different bogs featured in the study and

combining them together, but Lakkasuo proved to be the most reliable. A transfer function was produced using this training had an r^2, or the coefficient of determination, of 0.6. This was applied on the macrofossil data producing a water table reconstruction model using a WA-Tol model (Amesbury et al. 2016). The scripts used can be found in the appendix. Modern vegetation and water table data was collected from Lakkasuo in 2016 by PhD student Nicola Kokkonen.

4. Results

4.1 Chronologies

The ^{210}Pb dating was successful and produced accurate data (Table 2). The results were plotted against their respective depths, giving a rough idea of accumulation of organic matter (Appendix B). The curves experience the most significant change between the early 1900's and to the mid-20th century. The difference between curve slopes in LIA and in modern material are substantial. During the last 20 years more than twice the matter has accumulated than in during the whole 19th century. Thus, leading to more carbon sequestered. However, some distortion of the data is due to the weight of existing bulk pressing down the deeper layers and the further state of decomposition. The ^{210}Pb activity experienced some instabilities, but generally the performance of these chronologies should be adequate for this study. ^{14}C-results indicate that the oldest subsamples are likely from the turn of 16th and 17th centuries (Table 1).

Table 1. ^{14}C results from the bottom of each core. Large margins of error and comparison to ^{210}Pb analysis reveals that something was amiss with the samples.

Sample	^{14}C Dates (AD)	95.4% probability 2 σ calibrated age ranges	Calibration curve
SLL	1695-1919	1695AD (18.6%) 1727AD 1812AD (16.4%) 1854AD 1867AD (60.5%) 1919AD	IntCal 13
SHL	1955	1955	Bomb 13 NH1
SLH	1656-1916	1656AD (18.0%) 1697AD 1725AD (51.2%) 1814AD 1835AD (6.0%) 1878AD 1916AD (20.1%) …	IntCal 13

Table 2. ^{210}Pb dating results and error margins as dates Anno Domini. SHL (Siikaneva High Lawn) subsamples are younger than most SLH (Siikaneva Low Hummock) subsamples.

Depth (cm)	SHL		SLH	
	Year (AD)	±	Year (AD)	±
1	2016.78	1.00	2015.92	1.01
2	2016.75	1.00	2014.92	1.07
3	2016.72	1.01	2013.84	1.11
4	2016.64	1.01	2013.04	1.15
5	2016.60	1.01	2012.40	1.16
6	2016.55	1.01	2011.79	1.17
7	2016.30	1.01	2011.20	1.18
8	2016.30	1.01	2010.70	1.18
9	2016.23	1.01	2010.03	1.19
10	2016.30	1.02	2009.26	1.21
11	2015.92	1.02	2008.51	1.22
12	2015.57	1.02	2007.59	1.23
13	2014.79	1.02	2006.51	1.25
14	2014.58	1.02	2005.36	1.27
15	2014.09	1.02	2003.88	1.30
16	2013.77	1.02	2002.02	1.33
17	2012.89	1.02	2000.31	1.37
18	2011.63	1.02	1997.89	1.41
19	2010.05	1.03	1994.90	1.46
20	2008.52	1.03	1991.36	1.52
21	2005.94	1.03	1987.07	1.58
22	2003.30	1.03	1982.64	1.65
23	2000.37	1.04	1977.47	1.71
24	1996.38	1.04	1972.44	1.76
25	1992.08	1.05	1967.20	1.80
26	1989.31	1.05	1962.02	1.86
27	1984.22	1.06	1956.84	1.90
28	1975.90	1.08	1951.34	1.97
29	1968.98	1.09	1945.29	2.06
30	1956.70	1.13	1939.71	2.12
31	1943.58	1.18	1932.01	2.30
32	1941.80	1.17	1921.53	2.56
33	1929.10	1.24	1908.82	2.76
34	1919.01	1.29	1896.92	3.00
35	1918.63	1.27	1882.88	3.49
36	1911.15	1.32	1864.08	4.59
37	1902.61	1.39	1834.66	7.20
38	1876.90	1.78	1798.83	15.02

4.2. Peat and macrofossil analysis

Results of macrofossil analysis showed that few species tend to dominate the ecology, while more marginal species appear sporadically. 18 taxa were identified, 9 of them *Sphagnum* sp. *S. fuscum, S. rubellum* and *S. papillosum* were most dominant species in their habitats. Vascular plants were mostly few in number and in diversity. Most prominent were *E. vaginatum, Carex* and *Drosera* species. Tree and shrub remains were uncommon, only few *Betula pubescens* leaves were identified (Appendix D). In addition to identified taxa, there were other remains that deserve to be mentioned. Different types of roots were found all over the core, excluding the surface. Light roots were common in all samples, but woody roots were much more sporadic in their distribution. Charred wood was extremely rare in the samples. Changes of great magnitude were found in all cores. Changes in peat decomposition level was also prominent.

My samples included numerous remains of animal life but unfortunately, identifying these mainly *Arthropoda* remains, were largely out of the expertise of the author. The most prevalent animal taxon was a collection of *Oribatida,* or moss mites, which appeared pretty much throughout all samples. Large amounts of tapeworms and tardigrades were also found alive in the samples, despite the freezing of the cores.

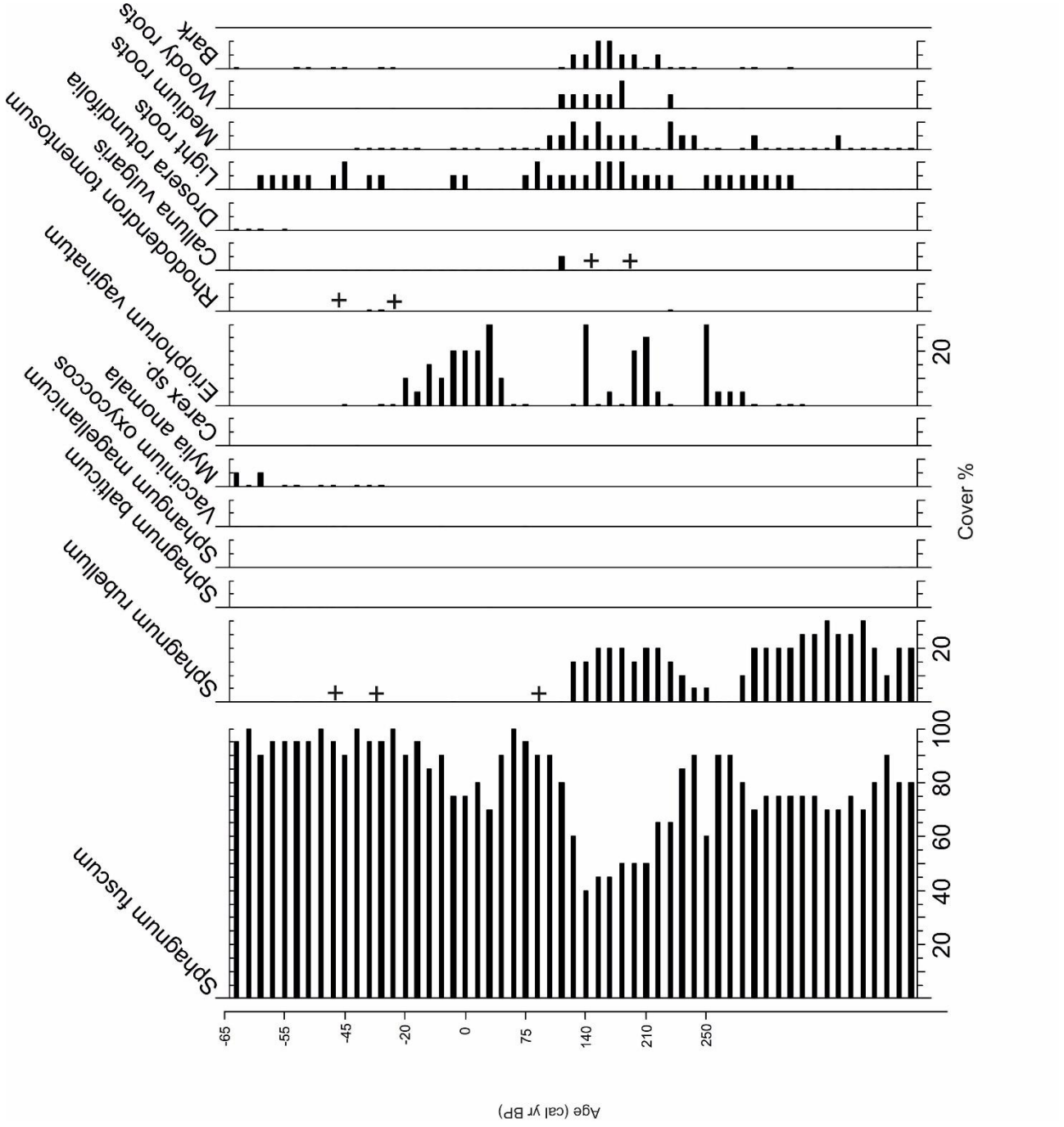

Figure 7. Siikaneva low hummock macrofossil analysis results. Rare occurrence of a taxon is displayed with a (+). Only selected taxa are shown. Bark is unidentified tree/shrub bark.

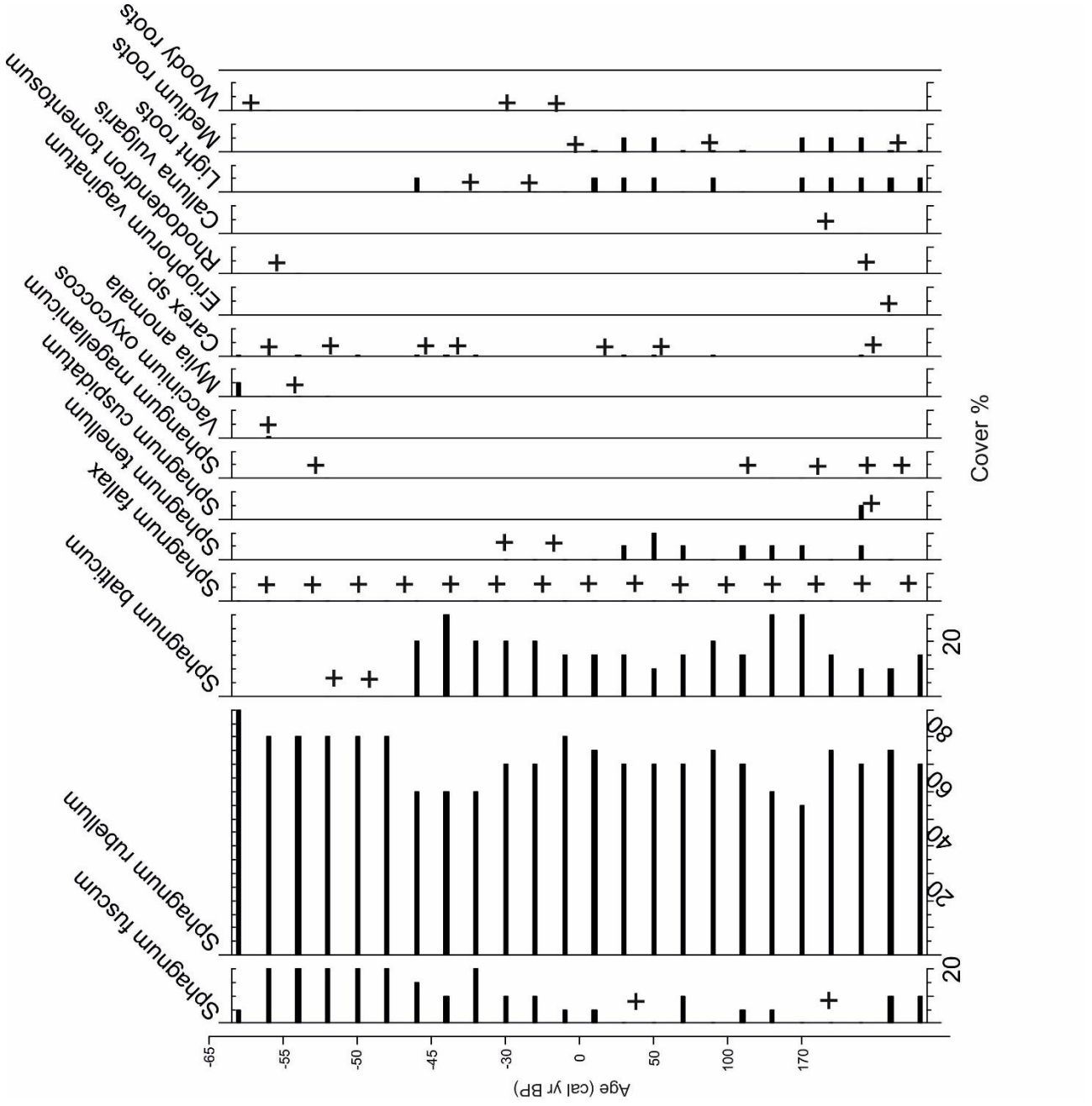

Figure 8. Siikaneva high lawn macrofossil analysis results. Rare occurrence of a taxon is displayed with a (+). Only selected taxa are shown.

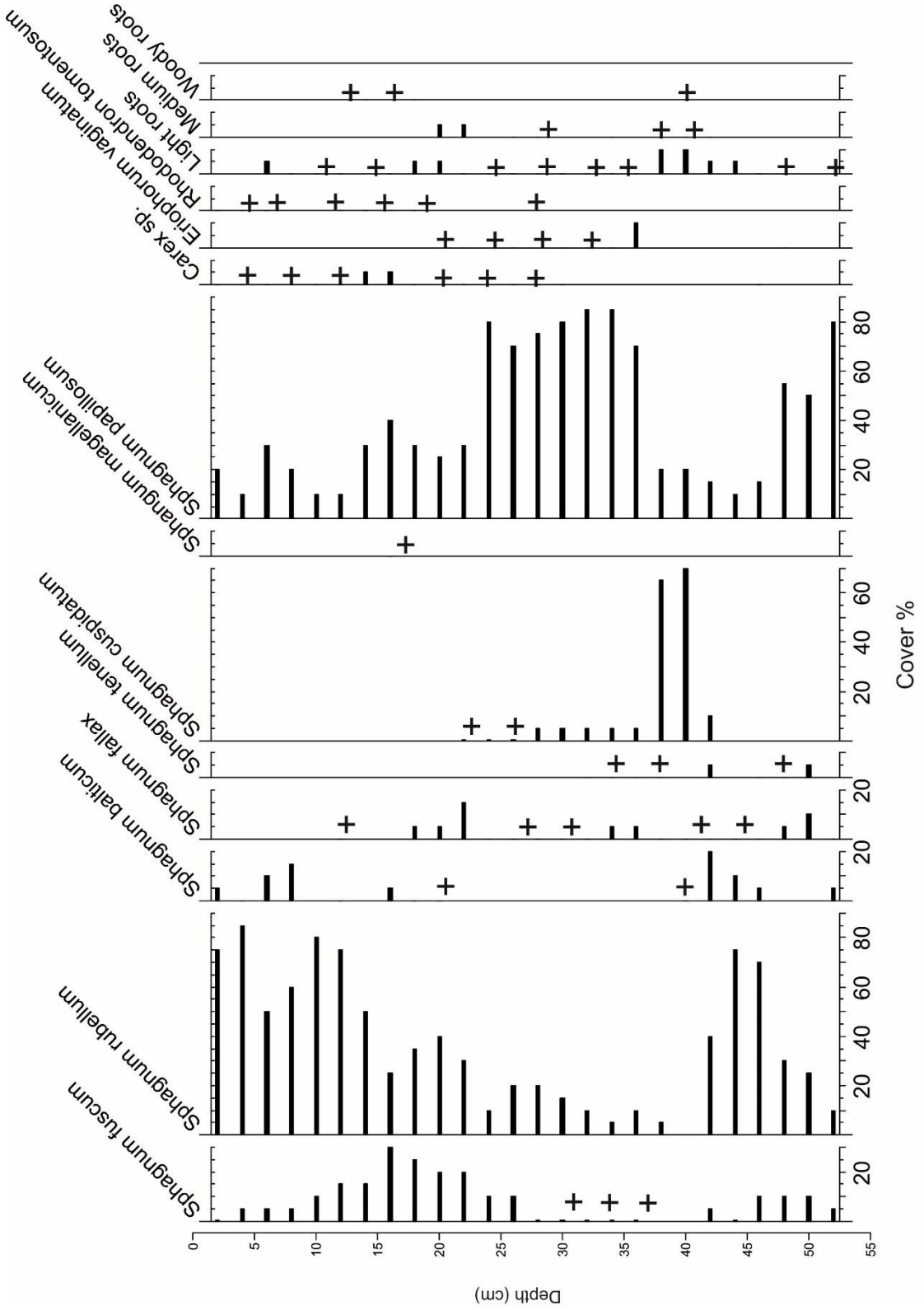

Figure 9. Siikaneva low lawn macrofossil analysis results. Rare occurrence of a taxon is displayed with a (+). Only selected taxa are shown.

In Siikaneva, past vegetation communities reflect the current habitats: low hummock (LH) profile is dominated by *S. fuscum*, high lawn (HL) by *S. rubellum* and low lawn (LL) by *S. rubellum* and *S. papillosum*. These species are dominant all the way until 1980's. In all three microhabitats, a period between 1980's and 1840, there is a clear change in vegetation. In LH *S. rubellum* has a strong presence that continues all the way to the bottom of the core (Fig. 7). In HL *S. fuscum* all but disappears, and is replaced by *S. balticum* (Fig. 8). In LL the percentage of *S. rubellum* clearly fell and it was replaced by mostly by *S. papillosum* and in lesser amount by *S. cuspidatum* (Fig. 9). *S. cuspidatum* first appears in LL data in the first half of 1800's and rapidly grows its percentage. At same time *S. rubellum* completely disappears from the data and returns only when *S. cuspidatum* rapidly declines in the mid 1800's to a more stable and low percentage. In the top of the cores several species were identified, that later disappeared totally. Species like *D. rotundifolia* and *M. anomala* were found only in the top 5 cm of the cores, almost without exception, and with relatively high proportionate coverage too. This rapid decrease of certain species is most likely due to their low resistance to decomposition.

Testate amoeba analysis from Siikaneva gives further insight to wetness dynamics (Appendix C). Z-score in Siikaneva is lowest (wet) at the bottom of the LH. From there z-score and a drier phase follows that lasts up to the 21st century. HL is much more varied. Stages are similar to LH, but are more pronounced. Around 40 cm, a sharp decline toward wetter conditions emerges. After a wetter period, z-score starts to rise, only to fall again at 15 cm. Here, z-score falls, rises and falls again in a span of a decade. Z-scores bounces up again and high values continue to this day. Overall, testate amoeba supports the macrofossil data on the conclusion that large-scale climate shifts have coincided and probably been an important factor in the development of peatland ecology after the LIA.

Figure 10. Examples of plant macrofossils. Starting from upper left, *Calluna vulgaris, Andromeda polifolia, Eriophorum vaginatum* tissue*, Sphagnum balticum* branch leaf*, Sphagnum rubellum* stem leaf and *Sphagnum magellanicum* branch leaf. Magnification in four last pictures is x100 and the red color in the bottom three is due to a dye used to make it easier to identify cell structures from individual hyaline cells. © Joonas Alanko

Peat bulk density in Siikaneva had clear marks of abrupt changes. In all cores a trend of rising bulk density towards greater depth was present. In surface subsamples bulk density was 0.04232 g/cm^3, 0.04404 g/cm^3, 0.04154 and the deepest subsamples results were 0.05476 g/cm^3, 0.04680 g/cm^3 and 0.05116 g/cm^3 in LH, LL and HL, respectively (Fig 11). This is expected as the mass of accumulating peat presses downwards and deeper peat layers are forced into a denser composition. However, between depths 29-45 cm all cores showed a much more substantial change in peat density. LH and HL records a rise in peat density in 30-35 cm, and simultaneously LL drops in density. After this, in 39-44 cm, LL rises to more than triple of its previous density. The 30-35 cm area dates roughly on the latter half of the 19th century, and 39-40 cm to the first half of said century. C/N analysis revealed a negative trend in values towards the bottom of the core (Fig. 11). Only in the bottom of cores the values again rose

quickly. In depths 17-45 cm in LL, 21-45 cm in LH and 29-33 cm in HL values were continuously below 60. Median was 61.62 and average 68.54.

Bulk density analysis revealed only one distinct anomaly. In all cores but one, there was a rise in density around the depths 30-40 cm, the depth slightly differing between cores. This anomaly was more prevalent in low lawn than in other microhabitats. Not much can be derived from this result, but it is important to note that in chronology it follows right after the largest changes in the macrofossil composition. This suggests, that whatever was behind said change, also left its mark on the density in the peat density. C/N analysis produced results that show a lot of variation between subsamples, but the only congruent results is that C/N ratio declines towards all core bottoms.

Level of decomposition also varied greatly within each core. Majority of the subsamples comprised of material, which had a low level of decomposition. *Sphagnum* remains often made 90 % of coverage in the subsamples. Close to intact plant specimens were abundant almost throughout the cores, accompanied by large amounts of individual stem and branch leaves (Fig. 10). However, every core included a region approximately 10 cm thick, where organic matter was much further decomposed compared to subsamples above and below. This region in the cores expanded from 27 to 36 cm in SLH, 24 to 34 cm in SHL and 30 to 44 cm in SLL. The change in organic matter was so prevalent that changes in material was already noticeable in cutting the cores into subsamples. Sieving the samples proved difficult, as did the microscope work, due to the high amounts of unidentifiable detritus. Within these areas vascular plant remains, particularly unidentified material, such as bark, thick roots and leaves were much more abundant than anywhere else in the cores. In certain subsamples, their coverage was so high that little *Sphagna* could be identified. *Sphagnum* remains were mainly restricted to individual leaves and parcels of stems, while in the rest of the cores whole plant individuals were often intact. Material was also often wrapped by roots into dense spherical clusters which were challenging to cut open.

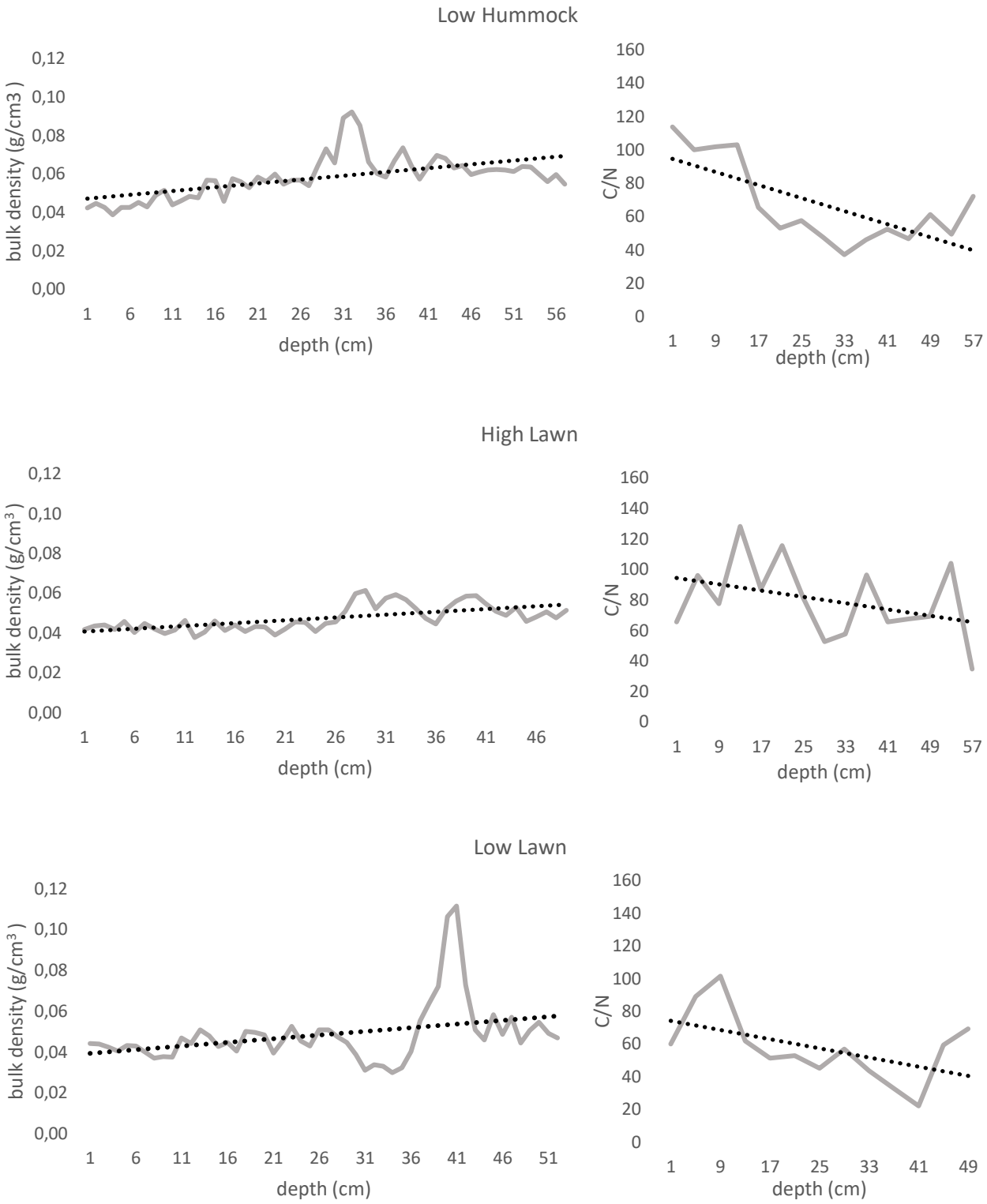

Figure 11. Siikaneva bulk density and C/N ratio. Dashed line indicates trend line in bulk density and in C/N-ratio.

4.3. Age-depth models

Water table reconstructions and age depth models were produced in order to create a series of reliable models of peatland development. Age-depth curves provided similar results from all sites (Fig. 12). Amount of cumulated matter has increased rapidly toward present time. Age-depth curve in Siikaneva samples suggests a definite rise in the production of organic matter. Rapid accumulation seems to have begun in just after the 1950's and has only accelerated since. After 1970's the age-depth curve is almost vertical and suggests a high accumulation rate. The rapid rise in the slope of the curves happens between 0 cal. BP, or 1950 AD and -50 cal. BP, or 2000 AD. Error margin varies between curves, but they all produce a similar result and are reliable towards the top of the cores.

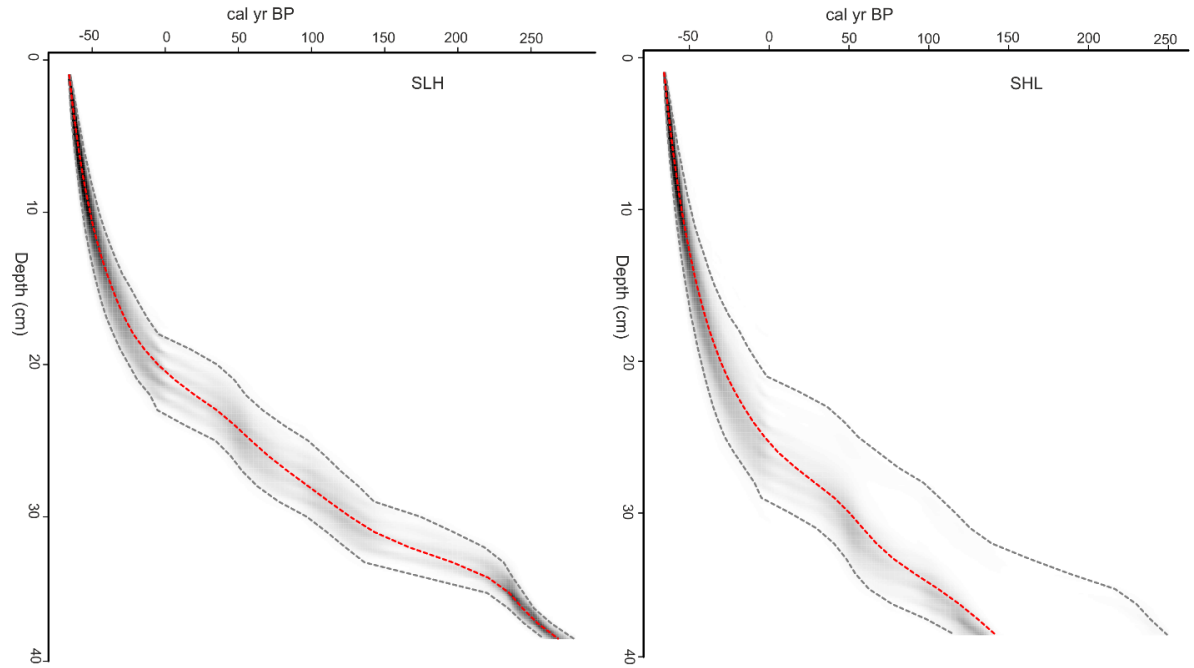

Figure 12. Age-depth models of Siikaneva low hummock (SLH) and high lawn (SHL) samples. Darker shades of grey indicate more likely calendar dates. Grey dashed curves indicate the 95% confidence intervals and the red dashed curve shows single most likely age-depth curve based on the mean age for each depth.

All age-depth models were produced with identical parameters. This resulted in varying accuracy. The 95% confidence intervals tend to grow toward core bottoms, but in SHL this was avoided and significantly more reliable result was produced. The percentage of provided dates within the 95% confidence intervals were 24 % in both Siikaneva cores. The curves do have considerable margins of error, especially in the bottom most depths. It is visible that however a curve within the 95% confidence intervals would be drawn, the result would still point toward

same type of trend. The model is a compromise in managing margins of error at different depths. However, it is still accurate enough to depict the accumulation trend in the time frame, but should not be treated as accurate to detail.

4.4. Water table reconstructions

Two water table reconstructions were produced from using modern vegetation in Siikaneva. Both models show a trend of declining water table level towards present day, although magnitude of drying and short-time fluctuations within the trend vary greatly between the models (Fig. 13). Low hummock and high lawn microtopographies were included in these reconstructions. In both bogs these topographic units showed distinct WT-levels. Low hummock had much lower and high lawn much higher WT-levels, indicating that these hummock and lawn patterns were prevalent throughout this study period.

Siikaneva cores present static first hundred years or so. All samples include growing amount of variation in the bottom depths, which are around 200 – 250 years old. Z-score is an index representing environment wetness. In results this means that negative values indicate drier peat surface and positive values wetter surfaces. The trend in my samples is toward a higher water table level. However, changes are relatively small and fluctuation happens does happen, making it difficult to establish a clear trend from these models alone. Both low hummock samples have consistently more negative water table levels than the high lawn samples.

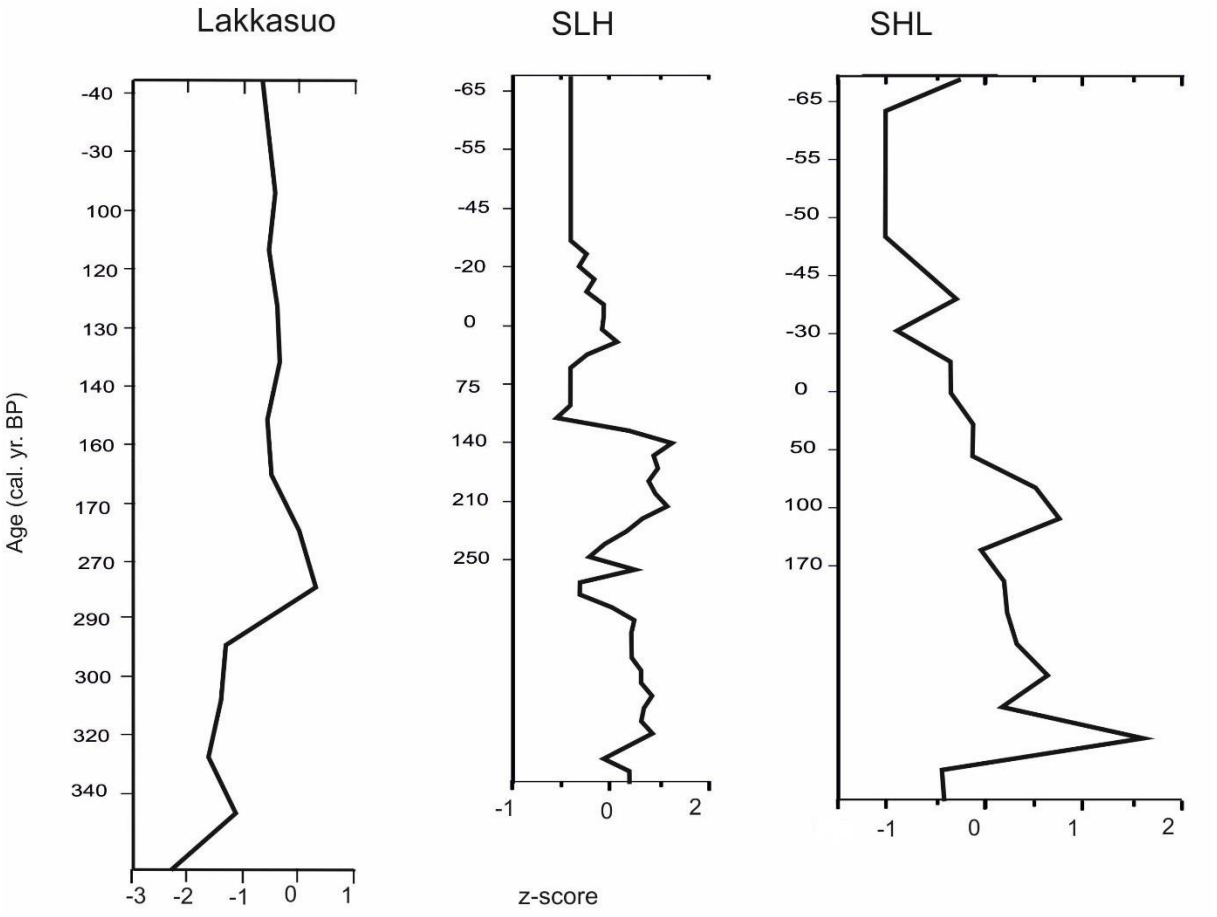

Figure 13. Water table reconstructions as z-scores from Siikaneva and Lakkasuo. From left to right: Lakkasuo, SLH (Siikaneva Low Hummock) and SHL (Siikaneva High Lawn). Samples are stable in their later stages, with larger shifts primarily in their earlier history.

Lakkasuo water table reconstruction has a distinct peak at 270 BP in wetness. Before this date, Lakkasuo seems dry and the rise toward a peak is not steady. After 270 BP conditions turn toward dryer environment, but do not all reach low figures as before the peak. However, conditions do keep drying to present day and progress is much more stable than in LIA conditions.

5. Discussion

My chronological results show proved that material has formed during the study period the post-LIA warming. Macrofossils and water table reconstruction models suggest significant changes in peatland surface wetness. Sudden increase of wetness in 1840's (160 cal. yr. BP), followed by drying during the last century reflect changes in climate. According to my age-depth models, the accumulation rates in peatlands have also experienced major changes in the study period. The link between peatland ecology and climate in the study sites is clear, and now the history of this relationship is visible through this study.

A pattern of change was found in peatland records, which answer my research questions. 1) The ending of LIA is visible in peatland records as a rapid change in vegetation composition by a surge of wet-habitat species. Similarly, warming periods are visible as an increase of dry-habitat species. Thus, I conclude that climatic changes indeed are visible in peatland records. 2) The initial bog response to the end of LIA was a shift toward wet habitat species. This reflects the increased moisture released to atmosphere and changes in global atmospheric and oceanic circulation. The subsequent warming has increased bog surface drying in a two-step pattern, with the latter being greater in magnitude and with a hundred-year intermission period in between. This intermission is characterized by slow drying of bog surfaces. The greatest turning points occur around 1850 and 1950. After the 1950's, the trend is towards a greater NPP and a dryer surface. 3) Increase of slowly decomposing vegetation, climatic change toward increasing growing season length and dryer peatland surfaces point towards a change. It is reasonable to assume, that northern peatlands will face increased pressure towards drying and ombrotrofication because of various changes in climate due to global warming. Depending on local water balance, this can either cause growing carbon sequestration, or threaten the peatland carbon stock.

Initial change was brought on by an increase in solar activity and a coinciding dip in volcanic activity (Bond et al. 2001; Wanner et al. 2008). Atmosphere and oceans began slowly warming, dismantling the climatic framework that held together the cold LIA climate (Crowler 2000). Here, my research points first to a response in peatlands, where much wetter conditions prevailed and accumulation rates began rising around 1850. A hundred-year period of steadily increasing carbon accumulation acted as a negative feedback for rising CO_2 levels in the atmosphere. As CO_2 levels have risen, the peatlands responded by taking in more and more carbon from atmosphere. This carbon has then accumulated in increasing amounts into

peatlands, but the water table has not risen at an equal rate. Gradual disappearance of wet habitat plant species ensued, as accumulation lifted the bog surface further away from the water table. After 1950, the same trend continued, but now with rapidly accelerating pace. Longer growth seasons ensured that carbon uptake grew rapidly as the peat accumulation increased and bog surfaces dried even more, leaving only the dry habitat species remaining. Growing GPP and increased accumulation of organic matter suggest a growing rate of carbon sequestration. Any sign of vascular plants having a foothold in the study area is not visible. However, previous research show that when water table levels fall below a threshold, the ensuing invasion of vascular plants is rapid (Strack et al. 2006). Vascular plants are capable of launching a positive feedback, where a quick succession of shrubs and trees further decrease water table levels leading to peatland drying, exposing the volatile carbon storage to the elements.

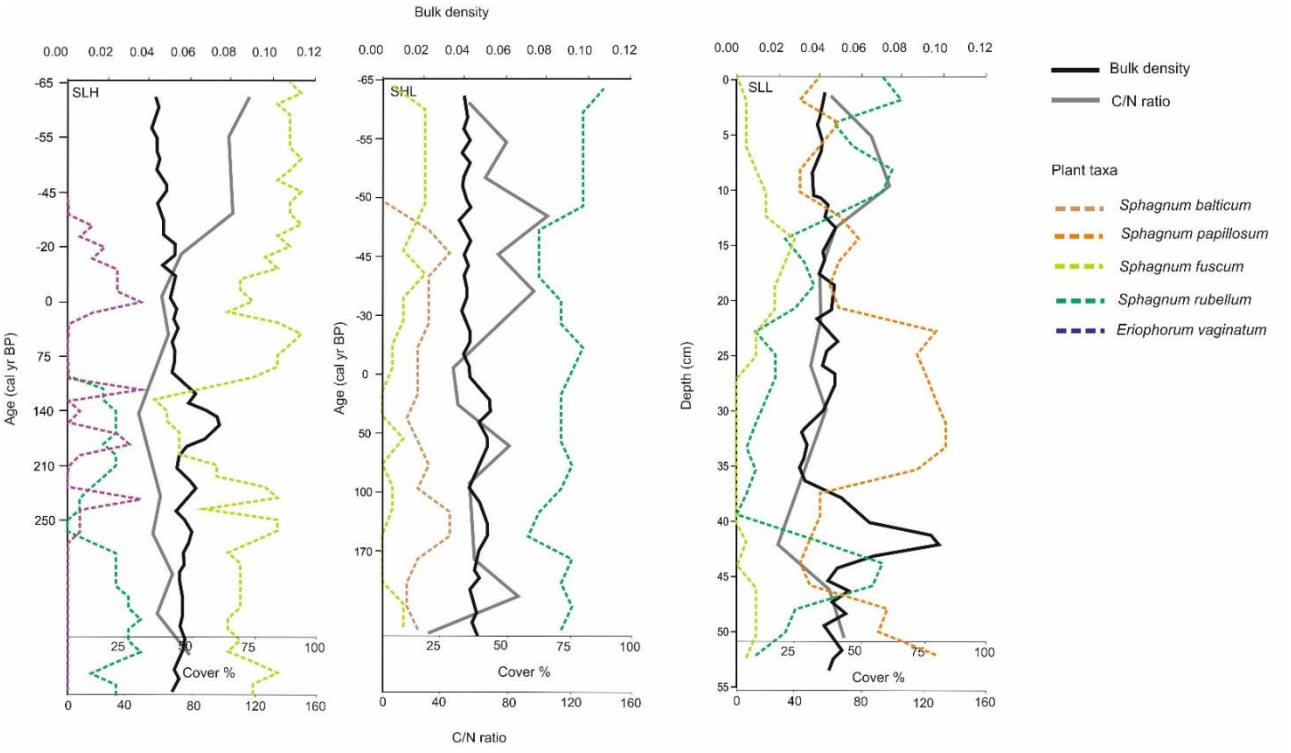

Figure 14. Bulk density, C/N ratio and selected plant taxa in Siikaneva (from left to right) low hummock, high lawn and low lawn. Disturbances can be seen in the lower part of the cores, *circa* 150 yr. BP, where LIA ended. There are clearly differences, in how readily different microhabitats react to changes in climate.

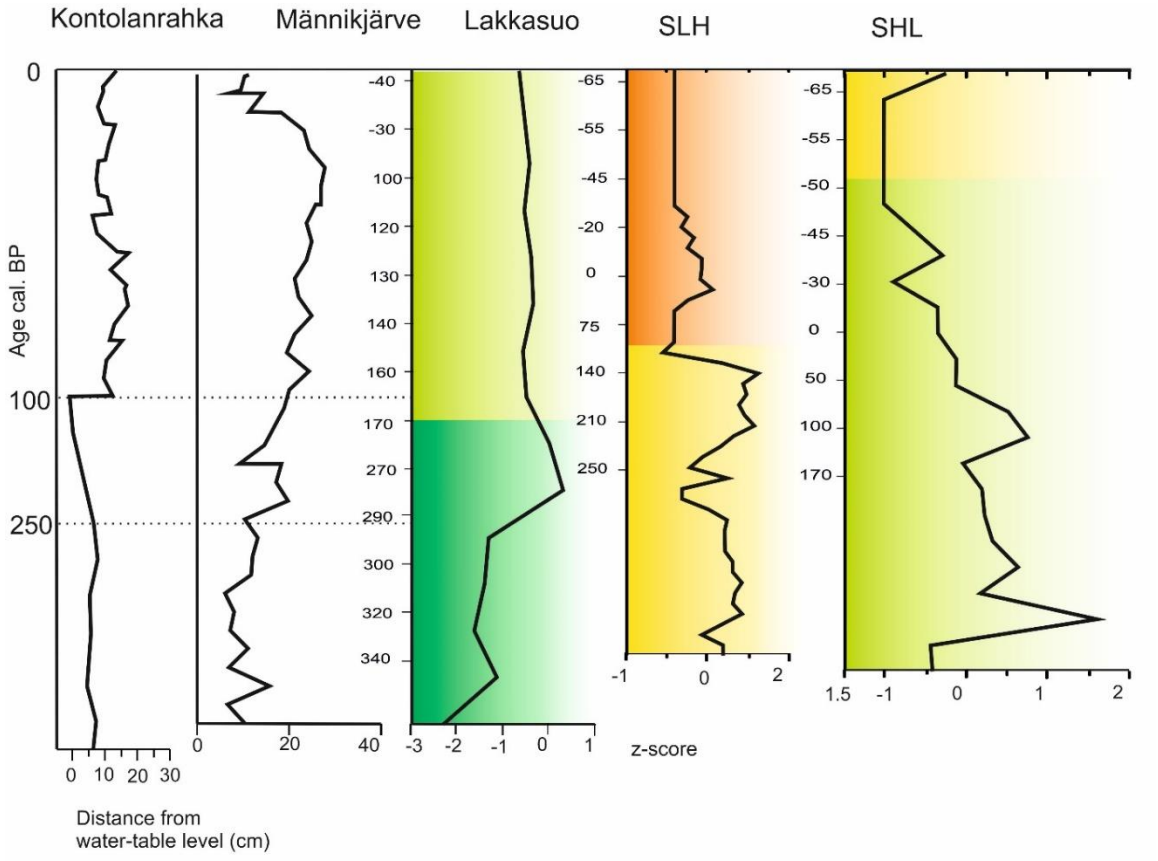

Figure 15. Water-table reconstructions (WTR) and macrofossil analysis across all study sites. Kontolanrahka and Männikjärve water-table –reconstructions (Väliranta et al. 2012) given as distance to water table surface, while others are in z-score. Lakkasuo WT-model is based on data from (Tuittila et al. 2007) Black curves are WT-reconstructions, and *Sphagnum* macrofossil assemblages are represented as different colors. Orange is *S. fuscum* dominated vegetation, yellow a combination of *S. fuscum* and *S. rubellum*, light green combination of *S. fuscum/S. rubellum* and *S. balticum*, and dark green for a *S. balticum* dominated with different dry habitat species. SHL Siikaneva High Lawn and SLH Siikaneva Low Hummock. In all study sites, vegetation composition has changed towards more dry-habitat species. All WTR's show great variation during the period associated with the end of LIA.

5.1. End of the LIA

The end of the LIA in my ^{210}Pb-chronology is dated to the 1840's AD (160 cal. yr. BP). Around this period, all study sites have gone through a visible change in plant composition and on most sites major anomalies in bulk density have been revealed. Study by Thornalley et al. (2018) revealed that at this time the Atlantic Meridional Overturning Circulation (AMOC) was weakened suddenly and has continued declining slowly ever since. In all three Siikaneva cores, changes in taxa composition is visible. Around this period, all microhabitats experienced

sudden increased wetness. All macrofossil samples react in unison in a period between 1840 and 1870 (160-130 yr. BP), or 35 -40 cm in depth. New taxa appear in great numbers and others seem to regress or vanish entirely. These rising species mostly regress or disappear themselves between 1940 and 1980, and in some cases, even faster.

Other cores seem to react with different magnitude than others. This suggests that different microhabitats react with different sensitivity. High lawn and low lawn are most affected, while low hummock shows much smaller changes. In low lawn, the increasing species, *S. cuspidatum* and *S. papillosum* are linked to wet conditions. *S. cuspidatum*, thrives in wet conditions, and its population seems to rise to dominance in the habitat rapidly, without any previous presence in the core. However, it disappeared almost as swiftly, regressing to a marginal species in a couple of decades, and then vanished. This suggest that around 100 years, conditions rapidly turned towards wetter conditions in low lawn, and even though change seems not to have been long lasting, some of the species adapted to more wetter conditions held their ground for a century.

In high lawn changes are not as dramatic as in low lawn. High lawn is a drier habitat than low lawn, where *S. fuscum* and particularly *S. rubellum* have more prevalent roles than in in low lawn (Fig. 14). Both drier habitat species regress beginning in 1870's, *S. fuscum* all but vanishing, but *S. rubellum* still maintains a large presence. Wetter habitat species S. balticum and S. tenellum increase in the same time. The macrofossil analysis reveals that significant changes in plant composition takes place close to the time, when I expected the LIA to end. Vascular plants and bryophytes more adapted to wetter conditions thrive for decades, but then receding in the course of 100 years. In low hummock *E. vaginatum* appears in large quantities roughly 200 years ago.

Climate change triggered the bog vegetation to a rapid response 250 years ago, coinciding with the end of LIA. This is visible in the water-table reconstructions as a peak of wetness (Fig. 15). A steadier trend of accumulation has been interrupted in the beginning of the 20th century. At the same time, C/N index started to grow and major fluctuations in bulk density and peat decomposition is visible. A study by Linderholm et al. (2018) seems to support this result, as a synthesis of several environmental proxies, including lake water levels, hummification, peatland water tables, and show increasing wetness after the mid-19th century in the Northern Atlantic region.

5.2 Warming

Species adapted to drier habitats take over first in the 1940's and 1950's (10 to 0 cal. yr. BP) and increase again just at the start of the millennia. Such a progression coincides well with what is known of climate history and suggests that during the first two warming phases, peatland drying was already happening. This also reflects the fact that this drying might be a result of the wet post-LIA period moving aside. At the same time, climate was warming as solar forcing grew and volcanic forcing faded (Crawley 2000).

Accumulation rates started to accelerate in the 1950's and have continued rising. This development coincides with the two latest warming phases and it is reasonable to assume the link between climate warming and rising rates of accumulation. This points to increase in more favorable climatic conditions, mainly longer growth season. At the same time, dry habitat species, *S. fuscum* and *S. rubellum* numbers start to grow in the latter half of the 20th century and gain dominant position in all cores after they were in decline in the 19th century and in the first half of the 20th. Some wet-habitat species disappeared and others became rare occurrences. *S. tenellum* only survives to the 1950's, whereas balticum disappears from the record only in the beginning of the 21st century. After this, *S. fuscum* and *S. rubellum* remain as the dominant species, with little or no competition. This progression coincides well with similar development in LL.

S. fuscum the dominant species throughout the whole LH core, while *S. rubellum* is clearly in a more marginal role. *E. vaginatum* is a species that tolerates a wide range of dry to intermediary conditions but cannot survive in a wet environment. *E. vaginatum* is associated with drying peat surfaces and ombrotrofication. This is the only example of sudden increase of a vascular plant in the dataset. *E. vaginatum* is a rare occurrence in earlier sumbsamples, but only gains a lot of ground during the two first warming periods. *S. rubellum* is associated with a wetter habitat than *S. fuscum*, but both species still belong to the driest parts of bogs. Around the 1940's *S. rubellum* vanishes again from the record, this time permanently, and at the same time *S. fuscum* increases to high levels. *E. vaginatum* disappears just as abruptly in the beginning the 21st century.

At the start of the third warming phase, climate began to warm with an increasing pace. Most likely because of the large amount of anthropogenic CO^2 released into the atmosphere. This led to a point, where probably due to growing evaporation and/or increasing peat accumulation,

the water table withdrew away from the bog surface. Subsequently drier species claimed the habitats at a rapid pace. In the last 50 years *S. fuscum* and *S. rubellum* have regained their previous dominance, fluctuating from time to time to even higher percentage than before 1840 (160 yr. BP).

A study by Linderholm et al. (2018) recognizes a recent drying phenomenon, coinciding with rapid climate change in the last few decades. In this study referred as the third warming phase, this fast drying is a potential threat to peatlands if water table levels fall too low. The data implies not only changes toward drier peatlands, but rapid changes as well. Frolking et al. (2011) concluded that climate forcing is the most important cause for change in boreal and the subarctic. They also stress the fact that not enough data exists on climate change effects on peatlands to create reliable models on future prospects. According to Laiho (2006) long term and short-term response to lowering water tables differ, because short term response is merely the old system adapting to new conditions. In the long term the old system is more likely to vanish completely, if dryer conditions ensue. This makes it difficult to model future peatland development, since the ecosystem might experience abrupt changes, making the presumptions of this system inadequate or even obsolete.

The critical factor for northern peatlands in the future is the regional development of hydrology. Studies on climate modelling suggest that as the high northern latitudes continue to warm at a rapid rate, global warming leads to rising sea temperatures, altering the courses and attributes of ocean circulation. As high latitude precipitation is mostly caused by the moisture carried by warm currents from the tropics, this will most likely lead to alterations in rainfall patterns in northern high latitudes. While some parts might receive increasing rainfall, other regions will have less precipitation. If rainfall and surface flow do not increase in par with growing accumulation, peatlands will face drying and ultimately forestification, which will sign end to carbon sequestration and might eventually lead to extensive carbon releases. In coming decades this change should become more and more evident and turn peatlands in certain areas into massive sources of carbon in to the atmosphere in from of CO_2 and CH_4. This will strengthen the greenhouse effect, warming the planet and leading to a positive feedback where carbon storages are drained and forests increase their presence in the arctic. In this scenario it seems unlikely that the slow negative feedback in remaining peatlands could significantly alter this trend after its release.

5.3. Uncertainties and error sources

A high-resolution study regarding the post-LIA peatland response has not been carried out before. Therefore, I do not have direct comparison for my results. I have however compared the results with more traditional, low-frequency studies in Kontolanrahka and Männikjärve. To ensure the most accurate and applicable results, all data in this study has been analyzed using the same methods. Other low-frequency studies have established that changes in peatland vegetation occur through the Holocene**.** High frequency studies suggest that peatlands undergo major changes if water table is lowered. Studies on modern peatland ecology points out that changes in peatland vegetation can take place rapidly (Minkkinen et al. 1999; Strack et al. 2006). This also has an immediate effect on carbon fluxes (Strack et al. 2004). Existing high frequency studies have typically concentrated on direct human impact on peatland hydrology by either water-level drawdown or restoration.

Margin of error in several peat analyses is mainly derived from human error and the composition of peat. Measuring, cutting, sampling and visual analysis of peat is partially subjective, as a person must rely largely on crude measurements and devices. The decomposed and largely elastic nature of peat makes it difficult to process both visually and physically. In case of macrofossil analysis, the identification of different plant taxa in partly decomposed material requires expertise and is always undermined by the level of decomposition. The physical process of cutting peat accurately, division into subsamples and measuring small volumes is challenging, and thus subjectivity comes to affect how accurately data is produced.

Testate amoeba is not entirely congruent to plant macrofossils as a proxy (Väliranta et al. 2012). Unlike plants, amoebas do have a limited capability of movement and a rapid life cycle. This means that amoeba community's response time is different from the plants. There are also differences in amoeba's ecological tolerances, as others are specialist and other generalists and thus the proxy value varies among species (Lamentowicz & Mitchell 2007). There are still uncertainties of the ecological niches of some species, further undermining their use as proxies (Mitchell et al. 2008).

This study points out the benefits of multi-proxy analysis. I used several proxies and dating methods that were available. This helped in identifying the most important parts and to discard random anomalies and noises from the large dataset. Using several methods is also an

insurance of kind, since in the course of scientific study, erroneous and inconclusive data is often the rule and not the exception. If anything, I should have incorporated more methods. Macrofossil analysis revealed large changes in the amount of unidentifiable organic matter (UOM). In this study, I did not measure UOM in any form. Retrospectively, it would have been better if such measurements were taken. In future studies analyzing UOM might produce interesting results. The amount of detritus could be a sign of changes in decomposition rate, and the conditions regulating decomposition in peatlands.

In an early phase of this study, I experimented in using more advanced technologies to slice peat into subsamples. A steel band saw was used to maximize the accuracy of subsample division, but contamination and loss of material made this method impossible to put into practice with the material. I also tested sectioning the peat sample to 0.5 cm subsamples to achieve even higher frequency, but the low amount of material left and decreased accuracy in cutting by hand made this impossible to implement in to the study.

Modelling is always a generalization of real circumstances, and always something is amiss with such a representation. I focused on creating a series of models that represent general trends, but do not necessarily represent accurately any single point in history. All age-depth models present significant variation in the 95% confidence interval, and clearly there are issues with accuracy in all models. All models point to similar development, although the accurate estimates of rate of accumulation is hard to pin down, especially before the 20th century. Thus, it is reasonable to assume that my results are a good representation of how these peatlands have developed in the last 250 years, even though I cannot claim to have accurately modelled details of said development.

Contamination is always a risk when handling samples fixed for chronological studies, from the extraction of peat in the field to the final preparations for analysis. My study made the best possible efforts in order to avoid any contamination, whether plant material or elements. All analyses, where contamination was a risk, were carried out in laboratory conditions in university premises.^{210}Pb-dates matched expectations and apart from few accidents, all subsamples made it through the dating analysis. Resulting chronology shows that the top of 40 cm of the cores have formed approximately in the last 230 years. The results were congruent enough to show a solid, logical chronology, with no anomalies or problems. Such logical results

make the chance of contamination improbable, although there is no way to be 100 % certain that the dates really match the age of the material.

^{210}Pb chronology gives a possible insight to peatland accumulation history. Dates reveal a pattern, where most of the organic stratigraphy has been produced in a relatively short period of time. During the last 100 years accumulations seems to have rapidly increased. This result is affected by the fact that deeper layers of peat are denser due to the pressure caused by the mass of layers above. However, it also coincides well with the expected climate warming after the LIA. It is possible that in the ^{210}Pb chronology the development of accumulation, and thus NPP in the peatland history, is already visible. It is important to recognize, that although these changes coincide with known changes, one cannot directly assume cause and effect. Causation does not equal correlation and one should compare these results to others.

The ^{14}C chronology had to be abandoned due to results that it much conflicted the much more trustworthy ^{210}Pb chronology. The latter comprised of a much larger number of samples as well and I chose to trust the latter. Five of the six ^{14}C-dated subsamples had margins of error between 200 and 300 years, and the sixth produced an age that was accurate but totally unacceptable. The sole accurate date re-analyzed and strange as it is, it produced the same result, ^{14}C age of -5 cal. BP, or 1995 AD. These results would mean that at least in the case of SHL, peat accumulation would include a discontinuity. However, since in peatland stratigraphy this happens only due to disturbance from peat surface, one cannot accept this as a usable result. Large margins of error make the other ^{14}C dates also highly untrustworthy. Thus, ^{14}C-dates were discarded from further use in the analysis. Such inaccurate and erroneous results suggest that contamination had taken place somewhere along the line. This is not an unlikely scenario, as the core bottom is the most vulnerable place for contamination, as it is not protected by other layers of peat, exposing it to modern carbon ever since the extraction from the study site. ^{14}C-analysis is also much more sensitive to modern carbon than ^{210}Pb is to modern lead.

Another issue affects chronological studies of larger areas. The results have to be extrapolated in order have a picture of regional and not only local climate history. The spatial resolution of this study is such, that only a handful of samples depict the history of large bogs and then are extrapolated to areas with similar conditions. Such generalization of results withholds a large margin of error. However, stated methods have been thoroughly accepted, practiced and

perfected by different study groups in the course of decades (Hughes & Barber 2003; Roulet et al. 2007; Väliranta et al. 2012), to give as accurate results as possible. This also makes the data compatible with older studies. It is important to note that few alternative methods exist and they too contain risks, albeit different types. Using old and well-defined methods the study is exposed to certain level of subjectivity, but within margins that are familiar from previous studies, making it a calculated risk.

Across all samples the trend has been toward a drier peatland surface, although individual shifts from dry to wet also occur. The much larger Siikaneva might be able to buffer environmental changes due to its large area. Low hummock has consistently lower WT values than high lawn. Since lawn-hummock microtopography is considered lasting, this is an implication that the modelling has been successful. However, since the water-table reconstructions have not proven as reliable as possible, I cannot assume these results to be accurate. Instead they give valuable information on large scale trends and proxy data should be applied to back up these models.

Männikjärve and Kontolanrahka water-table reconstructions were produced in a previous study (Väliranta et al. 2012). Kontolanrahka produced similar results to the two other Finnish bogs, albeit with greater fluctuations. Männikjärve however, situated across the Gulf of Finland, has a significant dip towards a drier a surface in the latest samples. This sudden dip is preceded by a hundred-year old trend of rising water table, which is also unlike any of the other samples. This suggests that a bog further south has had a different response to the latest phase in climate warming. Earlier development in Männikjärve is similar to other study sites, but it seems to be generally more prone to fluctuations than its northern counterparts. As Männikjärve is by far the southernmost site in the study, it is difficult to say, whether this is a causation of local environmental attributes, or represents a trend.

6. Conclusions

This study brought forward clear signs of climate-related responses in peatlands. It is now evident that high-resolution studies can identify climate change responses in peatlands through various proxies. My most significant results are the ^{210}Pb chronology, age-depth models, water-table reconstructions and macrofossil analysis. Peatland response is best visible in macrofossil data, and it is supported by testate amoeba analysis and water table reconstructions. Paleoclimatic studies have defined clear limits for the end of LIA and for subsequent changes in climate in the high northern latitudes. ^{210}Pb chronology shows that the significant changes in the data coincide with the end of LIA and the following warming periods. Using older, low-resolution data gave the study more spatial scope. Together, they allow to be determined that change in peatland vegetation and ecology coincide with known shifts in northern hemisphere climate. I am also able to claim that these changes have greatly affected the carbon dynamics in the study area and resembling environments across the boreal bioclimatic zone.

Future studies should expand the scope of high resolution, multi-proxy studies of peatland response to global warming. As this study is limited in its area, more data should be gathered in further studies from other regions to test, whether the pattern I recognized is truly a circumboreal response, or just a regional phenomenon. Due to differences in accumulation rates, the resolution of record possible to extract from a peatland varies. Studies should include peatlands across a range of southern boreal to arctic in order to gain comprehensive image of how peatlands are responding to climate change. In high arctic, accumulation in peatlands is slow, and small-scale changes may not remain visible in such a record. In ombrotrophic peatlands the accumulation rate is high enough to record small scale changes. Ecological factors, such as ecological succession, could also be studied.

Now we have a high-resolution view of the past changes in the peatlands, which suggests we seem to be approaching a tipping point in bog ecology. The future of northern high latitudes is complex and will most likely have alternating patterns of change in different areas. As northern peatlands across the arctic and boreal regions all phase climate warming, they experience growing NPP, which leads to increased accumulation. Thawing permafrost will free old peatlands, returning them to the carbon cycle. Ombrotrofication will advance further north, reducing the significance of surface flow and making the peatlands more dependent on precipitation, decreasing biodiversity and increasing carbon sequestration.

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Appendix

A) R-Scripts

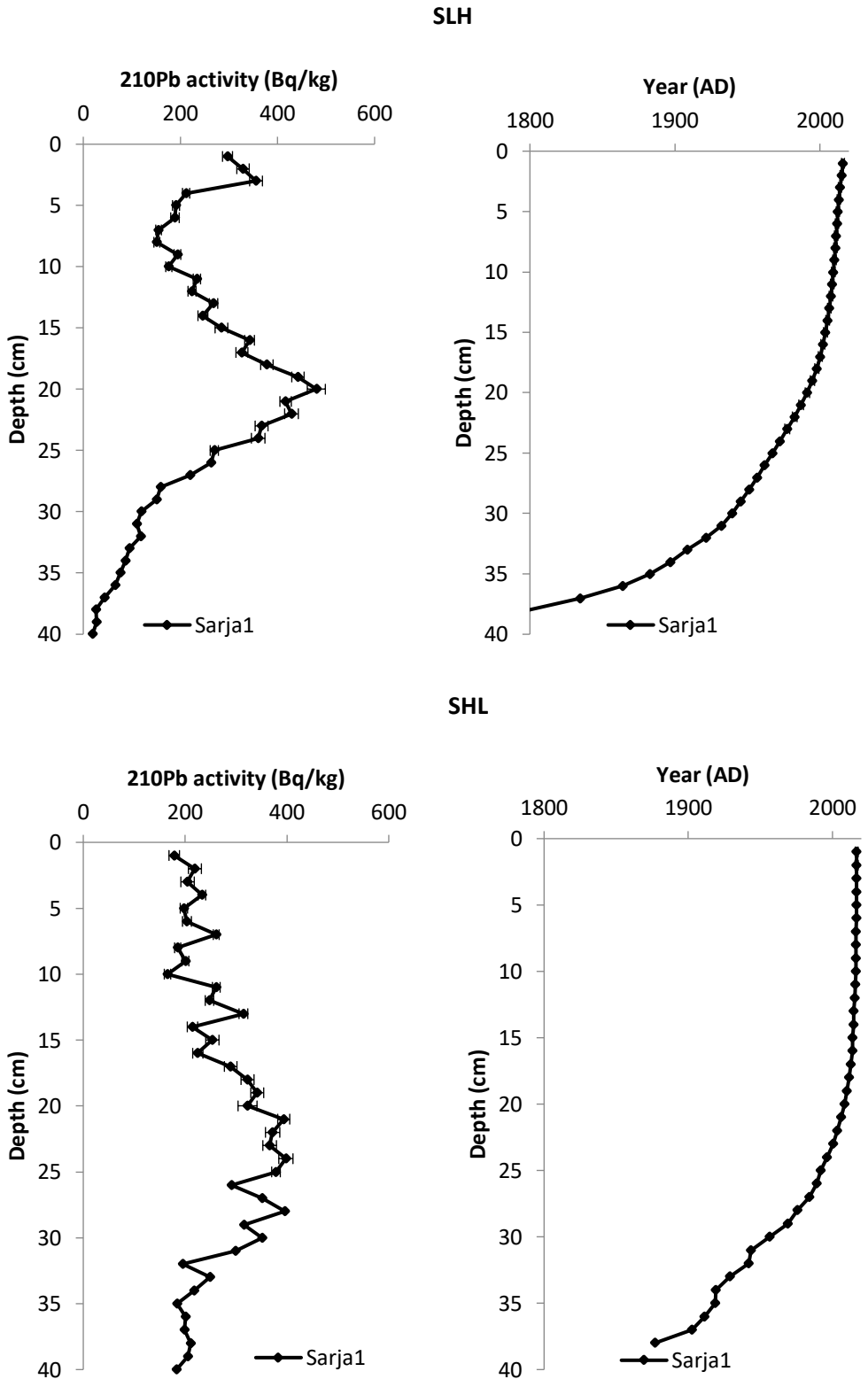
A1) Age-depth models

```
> install.packages('rbacon')
> library('rbacon')
> setwd('//ATKK/home/j/jbalanko/Desktop/gradu/TheData')
> Bacon_runs()
> Bacon('SHL', postbomb = 1,thick = 0.4, MinYr = -66)
n
y
```

A2) Water-table reconstructions

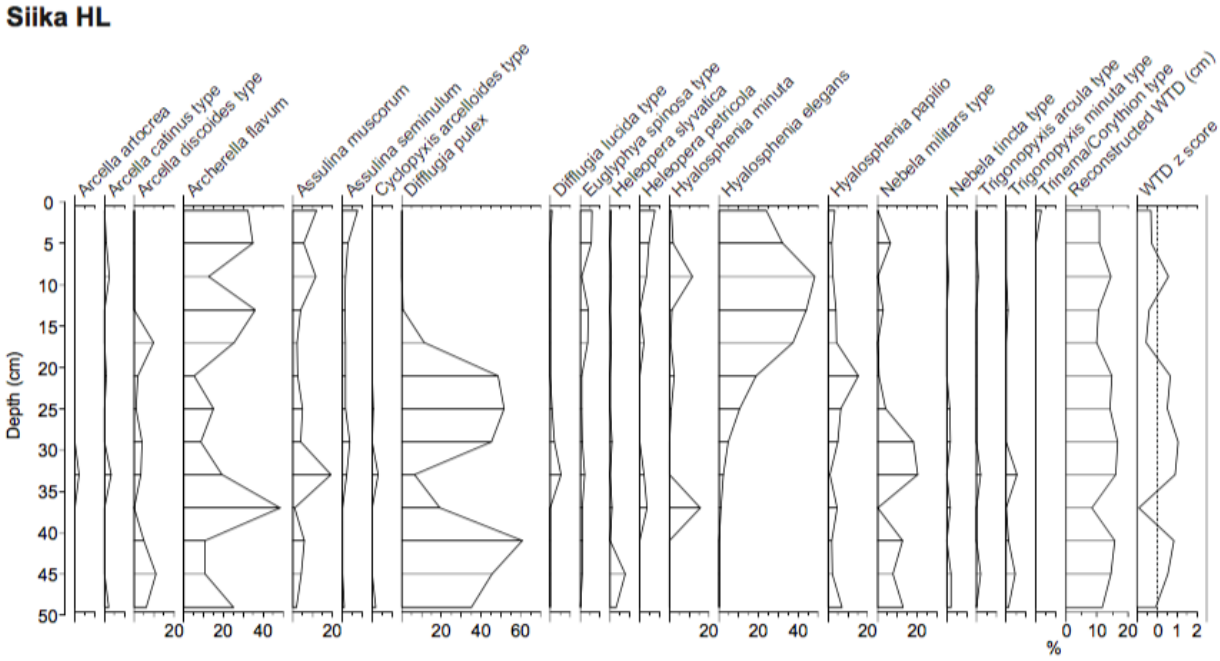
```
> setwd("INSERT LOCATION OF YOUR WORKING DIRECTORY")
> install.packages("rioja")
> library(rioja)
> EuroTF <- read.csv("EuroTF.csv")
> Spec <- EuroTF[,9:55]
> WT <- EuroTF$WTD  EuroTF_model <- WA(Spec, WT, tolDW=TRUE)
> EuroTF_model.cv <- crossval(EuroTF_model, cv.method="loo")
> performance(EuroTF_model.cv)
> Fossil <- read.csv("LakkaHL.csv")
> Fossil_spec <- Fossil[,6:31]
> EuroTF_recon <- predict(EuroTF_model.cv, Fossil_spec, sse=TRUE, nboot=1000)
> recon <- EuroTF_recon$fit.boot
> error <- EuroTF_recon$SEP.boot
> write.csv(recon, file="LakkaHL_recon.csv")
> write.csv(error, file="LakkaHL_error.csv")
> install.packages(c("R.basic"), contriburl="http://www.braju.com/R/repos/")
> library(R.basic)
> z <- zscore(recon)
> write.csv(z, file="LakkaHL_recon_z.csv"
```

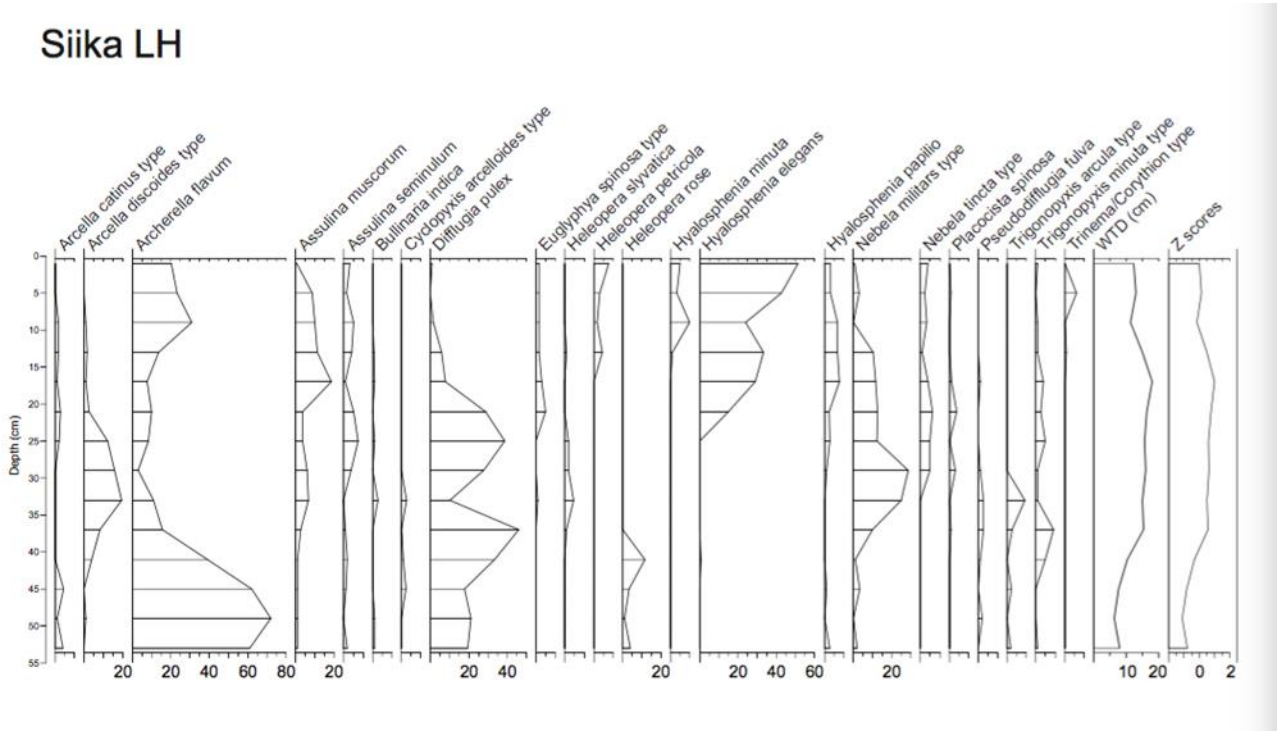
B) ^{210}Pb dating figures



Siikaneva ^{210}Pb dating results plotted on their respective depths and activity of ^{210}Pb as Bq/kg.

C) Testate amoeba figures





Testate amoeba analysis of Siikaneva high lawn and low hummock cores. Z-score curves look different between the bogs, but the wetness dynamics are actually similar and coincide with each other. Differences in accumulation rates make the curves look apart. Analysis was performed by PhD student Hui Zhang.

D) List of different taxa identified in the macrofossil analysis.

Plant group	Identified species
Bryophyta	
	Sphagnum rubellum
	Sphagnum fuscum
	Sphagnum balticum
	Sphagnum fallax
	Sphagnum tenellum
	Sphagnum cuspidatum
	Sphagnum angustifolium
	Sphangum magellanicum
	Sphagnum papillosum
	Mylia anomala
Vascular taxa	
	Betula pubescens
	Calluna vulgaris
	Carex sp.
	Drosera rotundifolia
	Eriophorum vaginatum
	Rhododendron tomentosum
	Vaccinium oxycoccos